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Refinement of Foam Backfill Technology for Expedient Airfield Damage Repair

Phase I: Laboratory Evaluation of Foam Materials

Luke Gurtowski, Mariely Mejías-Santiago, Christopher Griggs,
Jared Johnson, Bryan Ruiz-Cruz, and Deborah Felt

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Refinement of Foam Backfill Technology for Expedient Airfield Damage Repair

Phase I: Laboratory Evaluation of Foam Materials

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Abstract

This report focuses on the laboratory study to evaluate a number of foam materials for their suitability as crater-backfill materials. Seven foam formulations were evaluated between the summer of 2015 and the spring of 2016. Four of these materials were commercially available. The remaining formulations were designed specifically to support this project. The materials were analyzed for compressive strength, reactivity, and expansion ratio, in addition to other properties. Ultimately, two foam materials were identified and recommended for future development efforts at the field scale. All of the materials evaluated in this study were deemed hydro-sensitive, as the structure of the material and the critical properties for performance changed when the foam reacted in the presence of water. This issue should be addressed through contingent actions, such as isolation from water sources and adjustments to the formulation in future development efforts.

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Contents

Abstract	ii
Figures and Tables.....	v
Preface	viii
Acronyms	ix
1 Introduction.....	1
1.1 Background.....	1
1.2 Objectives.....	2
1.3 Scope of work	3
2 Experimental Program.....	4
2.1 Research approach	4
2.2 Materials tested.....	4
2.3 Specimen preparation.....	7
2.3.1 <i>Phase I</i>	7
2.3.2 <i>Phase II</i>	12
2.4 Reactivity.....	16
2.5 Density	16
2.6 Expansion ratio.....	16
2.7 Unconfined compressive strength.....	16
2.8 Hydro-insensitivity.....	18
2.9 Buoyancy	19
3 Test Results.....	20
3.1 Phase I	20
3.1.1 <i>Visual evaluation</i>	20
3.1.2 <i>Reactivity</i>	22
3.1.3 <i>Expansion ratio</i>	23
3.1.4 <i>Density</i>	24
3.1.5 <i>Compressive strength</i>	25
3.1.6 <i>Hydro-insensitivity</i>	27
3.1.7 <i>Buoyancy</i>	31
3.2 Phase II	31
3.2.1 <i>Visual evaluation</i>	32
3.2.2 <i>Reactivity</i>	34
3.2.3 <i>Expansion ratio</i>	36
3.2.4 <i>Density</i>	37
3.2.5 <i>Compressive strength</i>	37
3.2.6 <i>Hydro-insensitivity</i>	40
3.2.7 <i>Buoyancy</i>	43

4 Discussion of Results	44
5 Conclusions and Recommendations	47
References	49
Appendix A: Stress-strain Curves.....	50
Appendix B: Maximum Compressive Strength	60
Appendix C: Additional Hydro-insensitivity Figures	64
Report Documentation Page	

Figures and Tables

Figures

Figure 1. Chemical representation of a two-component 1A:1B rigid high density polyurethane.....	6
Figure 2. Specimen preparation process: A) Measurements of mass and liquid volume, B) Mixing of components, C) Foam curing process, and D) Specimens after unmolding process.....	8
Figure 3. NFCI Void-Filling System 24-020 specimens produced using inadequate mixing techniques. A) Profile view of heterogeneous specimens produced using initial procedure. B) Uncured bottom of specimen after premature unmolding.....	9
Figure 4. NFCI Elastomer System 24-077132 specimen. A) Solidification of material during transfer from can to cylinder. B) Profile view of completed specimen. C) Bottom view of completed specimen	10
Figure 5. HMI RR601 specimens prepared using manual mixing via tongue depressor. A) Profile view of specimens. B) Specimen 1 bottom. C) Specimen 2 bottom. D) Specimen 3 Bottom.....	11
Figure 6. HMI RR601 specimens prepared using electric mixer. A) Tops of specimens within cylinders. B) Bottom of specimen after unmolding.....	11
Figure 7. HMI RR601 specimens mixed in plastic cylinders using the air mixer. A) Profile view of specimens before and after unmolding. B) Bottom of specimen following unmolding. C) Crack generated during foam expansion and curing.....	12
Figure 8. Containers for materials used in Phase II. A) HMI RR601 container. B) Foam-iT! 10 Slow containers. C) PI Slow and PI Medium containers.	13
Figure 9. Foam specimens Foam-iT! 10 Slow (A), PI Slow (B), and HMI RR601 (C) produced using low-to-moderate rotational speed via pneumatic mixer with axial impeller.....	14
Figure 10. Phase II HMI produced via 30 sec of low-to-moderate agitation using pneumatic mixer.....	15
Figure 11. Instron Machine used for compression strength testing.....	17
Figure 12. Foam-iT! 10 Slow samples formed in dry plastic cylinders. A) Full sample after removal from cylinders. B) Specimen prepared for UCS testing. C) Bottom of specimen prepared for UCS testing.....	21
Figure 13. NFCI Void-Filling System 24-020 samples for analysis. A) Full samples produced using the recommended procedure and cured overnight for analysis. B) Bottoms of overnight-cure samples produced for analysis.	22
Figure 14. HMI RR601 samples prepared in metal can using an air mixer: A) Sample after unmolding, B) Cut created during the expansion of the foam and C) Bottom of sample after being unmolded.	23
Figure 15. Average expansion ratio of three products with 1-hr and overnight cures.	24
Figure 16. Phase I foam density data.....	25
Figure 17. Comparison of Phase I density and expansion ratio data.....	25
Figure 18. Compressive strength results for three Phase I formulations.....	26

Figure 19. Foam-iT! 10 Slow specimens formed with water present in the plastic cylinders. A) Full specimens after removal from cylinders. B) Specimen expanding within water in cylinder. C) Bottom of Specimen 1-W.	28
Figure 20. NCFI 24-020 Specimens. A) First specimen before unmolding, B) Bottom of another specimen and C) Bottom of the first specimen.....	29
Figure 21. HMI RR601 specimens prepared with 1/2 in. of water in the bottom of the cylinder: A) Specimens after being unmolded and B) Bottom of the specimens.....	30
Figure 22. Foam-iT! SLOW specimens produced during Phase II.....	33
Figure 23. Visual comparison of pneumatically mixed Foam-iT! SLOW specimens produced using two preparation methods.....	33
Figure 24. Phase II HMI Batch 1 specimens.	34
Figure 25. PI specimens. A) PI Slow. B) PI Medium.....	34
Figure 26. Bottom of PI Medium specimen displaying small voids. These voids were observed on several specimens regardless of formulation.	35
Figure 27. Stress-strain curves for Phase II foam formulations.	38
Figure 28. UCS versus cure time.	39
Figure 29. Interior of hydro-insensitivity specimen.	41
Figure 30. Hydro-insensitivity samples: A) Foam-iT! 10 Slow, B) Phase II HMI, C) PI Slow, and D) PI Medium.	42
Figure 31. Bottom of PI Slow hydro-insensitivity specimen.	42
Figure A1. Phase I Foam-iT! 10 Slow overnight cure (dry) stress-strain curve.....	50
Figure A2. NCFI Void-Filling System 24-020 overnight cure (dry) stress-strain curve.....	50
Figure A3. HMI RR601 overnight cure (dry) stress-strain curve.	51
Figure A4. Phase II Foam-iT! 10 Slow overnight cure (dry) stress-strain curve.....	51
Figure A5. Phase II HMI Batch 1 overnight cure (dry) stress-strain curve.	51
Figure A6. Phase II HMI Batch 2 overnight cure (dry) stress-strain curve.	52
Figure A7. Phase II HMI Batch 3 overnight cure (dry) stress-strain curve.	52
Figure A8. PI Slow overnight cure (dry) stress-strain curve.	52
Figure A9. PI Slow overnight cure (dry) stress-strain curve.	52
Figure A10. Phase II Foam-iT! 10 Slow 15-min. cure stress-strain curve.	53
Figure A11. Phase II Foam-iT! 10 Slow 30-min. cure stress-strain curve.	53
Figure A12. Phase II Foam-iT! 10 Slow 45-min. cure stress-strain curve.	53
Figure A13. Phase II Foam-iT! 10 Slow 60-min. cure stress-strain curve.	54
Figure A14. Phase II Foam-iT! 10 Slow 120-min. cure stress-strain curve.	54
Figure A15. Phase II HMI Batch 1 15-min. cure stress-strain curve.	54
Figure A16. Phase II HMI Batch 1 30-min. cure stress-strain curve.	54
Figure A17. Phase II HMI Batch 3 15-min. cure stress-strain curve.	55
Figure A18. Phase II HMI Batch 3 30-min. cure stress-strain curve.	55
Figure A19. Phase II HMI Batch 3 45-min. cure stress-strain curve.	55
Figure A20. Phase II HMI Batch 3 60-min. cure stress-strain curve.	55
Figure A21. Phase II HMI Batch 3 120-min. cure stress-strain curve.	56
Figure A22. PI Slow 60-min. cure stress-strain curve.	56

Figure A23. PI Slow 120-min. cure stress-strain curve.....	56
Figure A24. PI Medium 15-min. cure stress-strain curve.....	57
Figure A25. PI Medium 30-min. cure stress-strain curve.....	57
Figure A26. PI Medium 45-min. cure stress-strain curve.....	58
Figure A27. PI Medium 60-min. cure stress-strain curve.....	58
Figure A28. PI Medium 120-min. cure stress-strain curve.....	58
Figure A29. Phase II Foam-iT! 10 Slow hydro-insensitivity stress-strain curve.....	59
Figure A30. Phase II HMI Batch 3 hydro-insensitivity stress-strain curve.....	59
Figure A31. Phase II PI Slow hydro-insensitivity stress-strain curve.....	59
Figure A32. Phase II PI Medium hydro-insensitivity stress-strain curve.....	59
Figure B1. Kinetic maximum compressive stress.....	62
Figure C1. Bottoms of HMI RR601 hydro-insensitivity specimens.....	64
Figure C2. Bottoms of PI Slow hydro-insensitivity specimens.....	65
Figure C3. Bottoms of PI Medium hydro-insensitivity specimens.....	65
Figure C4. Bottoms of Foam-iT! 10 Slow hydro-insensitivity specimens.....	65

Tables

Table 1. Outline of tests for foam backfill materials.....	4
Table 2. Foam materials evaluated.....	5
Table 3. Foam component liquid densities.....	13
Table 4. Pass/fail criteria for foam hydro-insensitivity test.....	19
Table 5. Summary of Phase I results.....	20
Table 6. Reduction in physical properties for hydro-insensitivity specimens relative to the overnight specimens prepared without water.....	27
Table 7. Phase I buoyancy data.....	31
Table 8. Experimental results for Phase II.....	31
Table 9. Failure criteria for foam formulations based on GTP-8.....	40
Table 10. Quantitative hydro-insensitivity data for Phase II foam formulations.....	40
Table 11. Percent change on hydro-insensitivity specimens relative to the standard specimens produced in the absence of water.....	41
Table 12. Phase II buoyancy data.....	43
Table 13. Summary of technical data for foam formulations.....	46
Table B1. Phase I maximum compressive stress.....	60
Table B2. Strain at maximum compressive stress.....	60
Table B3. Phase I maximum compressive stress – overnight (dry) and hydro-insensitivity specimens.....	61
Table B4. Strain at maximum compressive stress – Phase II overnight dry) and hydro-insensitivity specimens.....	61
Table B5. Average maximum compressive stress – kinetic strength study.....	62
Table B6. Maximum compressive stress standard deviation - kinetic strength study.....	63

Preface

This study was conducted for the U.S. Air Force Civil Engineer Center under the Airfield Damage Repair Research and Development Program. The technical monitor was Dr. Craig Rutland, AFCEC. The Program Manager was Jeb S. Tingle, ERDC-GSL.

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COL Bryan S. Green was the Commander of ERDC, and Dr. Jeffery P. Holland was the Director.

Acronyms

ADR	airfield damage repair
AFCEC	U.S. Air Force Civil Engineer Center
APB	Airfields and Pavements Branch
ASTM	American Society for Testing and Materials
ERDC	U.S. Army Engineer Research and Development Center
ESMD	Engineering Systems and Materials Division
FOD	foreign object debris
GSL	Geotechnical and Structural Laboratory
GTP	Geotechnical Test Procedure
HMI	Hydraulic Mudpumps Inc.
hr	hour
IED	Improvised explosive device
min	minute
NCFI	NCFI Polyurethanes
NYDOT	New York Department of Transportation
lb/ft ³	pounds per cubic foot
PI	Primal Innovation
psi	pounds per square inch
RS	rapid setting
rpm	revolutions per minute
sec	second
UCS	unconfined compressive strength
USAF	United States Air Force

1 Introduction

1.1 Background

Since 2004, a number of airfield damage repair investigations have been conducted at the U.S. Army Engineer Research and Development Center (ERDC) under the U.S. Air Force's (USAF's) Airfield Damage Repair (ADR) Modernization program. This program has resulted in the development of a wide range of pavement repair alternatives that could be used across the full spectrum of military operations. The repair alternatives developed during this time included a foam backfilled repair capped with rapid-setting concrete material. Laboratory and field tests conducted during 2006 through 2009 indicated that the combination of a rapid-setting material over rigid polyurethane foam reduced the time of repair, required equipment, and materials needed to backfill craters compared to using compacted soil or aggregate (Priddy et al. 2007).

The early foam research was conducted in 2006, and results indicated that the foam material possessed several characteristics that made it a good candidate for crater repair. The material expanded many times its package volume and provided unconfined compressive strength (UCS) values similar to well-compacted soil or aggregate. The foam material mixed easily, could be placed with portable equipment, and had accelerated set times. As a result, the foam product yielded a temporary repair that was easily capped and withstood traffic within short time frames of repair.

In an effort to determine the optimal backfill product for crater repair, ten foam materials were evaluated for product reactivity, UCS, and density. These foam materials were also studied to determine the effect of environmental factors on foam placement. Temperature variations were tested, and 70°F was determined to be the optimal temperature for foam placement. The effects of soil moisture and standing water during placement were studied, and the compressive strength of the foam was significantly reduced when standing water or soil moisture was present. The use of plastic sheets to prevent foam contact with soil moisture resulted in difficulties during the installation process and created a slip plane within the foam structure, resulting in a weaker repair.

The effects of aggregate size in foam extensions on reactivity, strength, and density were tested in an effort to improve compressive strength of the final product. Results indicated that there was no significant improvement in the critical characteristics of the foam products with the presence of aggregates.

At the conclusion of the tests conducted by Priddy et al. (2007), Foam-iT! 10 Slow was selected as the best performing foam product among those tested based on the compressive strength and expansion ratio criteria. None of the foam products evaluated achieved 300 psi compressive strength (measured at 2 percent strain), which was the objective compressive strength for foam backfill materials (Priddy et al. 2016). However, Foam-iT! 10 Slow met the threshold compressive strength, 200 psi, used for foam material acceptance.

This down-selected foam product was then used in conjunction with a rapid-setting concrete cap in a number of full-scale field tests to determine if the foam backfilled crater repairs could support a limited number of simulated F-15 and C-17 aircraft traffic passes (Tingle et al. 2009 and Priddy et al. 2010). The repairs supported between 80 and 1,800 passes of either aircraft, depending on concrete cap thickness. The repair technique was ultimately certified under actual aircraft traffic in 2009 using both F-15 and C-17 aircraft (Priddy et al. 2013). Despite these promising field test results, the foam backfill repair technique was not recommended for acquisition due to issues identified during field experiments including foam material moisture sensitivity and dispensing equipment clogging issues. Refinement of both the foam material and the foam mixing and dispensing equipment was recommended (Priddy et al. 2016).

1.2 Objectives

As part of the new USAF “Lighter and Leaner” research and development initiative, the ERDC was tasked by the USAF to refine the foam backfill technology for expedient airfield damage repair. The specific objective of the research presented in this report was to evaluate new foam product formulations through laboratory testing to select the top performing product for further field testing.

1.3 Scope of work

Seven foam formulations were evaluated at the laboratory scale in this study. The properties specifically analyzed were

- Compressive strength
- Reactivity
- Expansion
- Density
- Hydro-insensitivity

The products were analyzed qualitatively and quantitatively. The following success criteria for the formulations were defined by the AFCEC:

- Expand to many times the packaged volume (objective 10 times liquid volume; threshold 6).
- The final expanded foam surface should be as even as possible with no visible cracks to avoid having to cut it prior to placing the capping material.
- Provide compressive strengths similar to well-compacted soil or aggregate (objective 300 psi; threshold 200 psi).
- React and set rapidly enough (5 to 30 min) to reduce repair time while still providing enough time to dispense the total required volume of product into the repair void before it starts reacting.
- Have accelerated effective cure times (objective 30 min; threshold 60 min), defined as the time from the initial blending of foam components until the foam had reached the threshold or target compressive strength.
- Contain moisture insensitive properties that produce negligible quantitative and qualitative differences between specimens produced with and without the presence of water.

The study presented in this report was separated into two laboratory testing phases. Results from the first phase guided the experimental design and procedures of the latter.

2 Experimental Program

2.1 Research approach

This project consisted of two phases that were separated based on the availability of materials and experimental procedures. The laboratory test program consisted of several experiments designed to obtain information needed to rank and determine which foam product was the optimal material for backfill during expedient ADR efforts. Table 1 illustrates the tests performed on each foam product, including the standard test method and the minimum number of specimens required by that standard.

Table 1. Outline of tests for foam backfill materials.

Property	Test Method	Minimum Required Replicates
Reactivity (Rise time and set time)	N/A	3
Expansion ratio	N/A	3
Compressive strength	ASTM D 1621-04a	5
Hydro-insensitivity*	GTP-8; GTP-9	3
Expansion ratio	N/A	3
Density	ASTM D 3574-05	3
Buoyancy	N/A	3

* Adapted from Geotechnical Test Procedures GTP-8 and GTP-9, New York State Department of Transportation.

2.2 Materials tested

The seven materials tested during this study are listed in Table 2 and included both commercially available products and foam formulations that were specifically design for this research study. Most products evaluated consisted of two components (Figure 1) that were held in separate containers. While the exact chemistry varied between products, the general composition was similar. Component A consisted of a polymeric isocyanate compound. Component B consisted of a blend of polyol compounds, catalysts, proprietary additives, and water. When the two components were mixed, chemical reactions immediately began to form a closed-cell, rigid polyurethane foam.

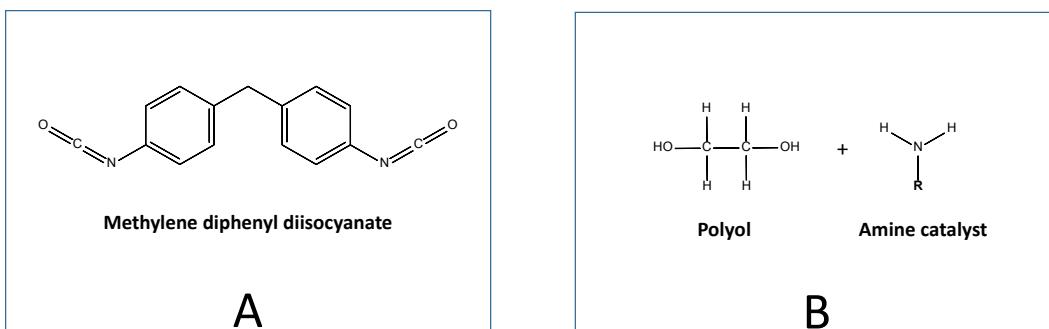
Table 2. Foam materials evaluated.

Product Name	Company	Product Type	Applications and Availability	Phase I	Phase II
Foam-iT! 10 Slow	Smooth-On	Two-component, rigid, high-density polyurethane foam	Backfill material for large industrial pours; commercially available	X	X
NCFI 24-020	NCFI	Two-component, rigid, high-density polyurethane foam	Void-filling applications requiring a high compressive strength; commercially available	X	
NCFI 24-077132	NCFI	Two-component, polyether, polyurethane elastomer, hydrophobic foam	Rock grout and soil stabilization; commercially available	X	
HMI RR601	HMI	Two-component, high-density, polyurethane foam	Concrete raising and soil stabilization; commercially available	X	
Phase II HMI (2015 Modification)*	HMI	Two-component, high-density, polyurethane foam specially formulated with a slower curing rate	Specially formulated for ADR project; three separate batches were analyzed		X
PI Slow	Primal Innovation	Two-part polymer foam with slow cure time	Backfill potholes and void spaces; prototype formulation		X
PI Medium	Primal Innovation	Two-part polymer foam with moderate cure time	Specially formulated for ADR project		X

* Three separate batches of this product were analyzed individually during Phase II.

Commercially available foam products included Foam-iT! 10 Slow, NCFI Void-Filling System 24-020, NCFI Elastomer System 24-077132, and HMI RR601. Foam-iT! 10 Slow is water-blown, rigid polyurethane designed to expand approximately 6 times its initial volume to produce a final density of approximately 10 lb/ft³. This material is formulated with a relatively slow reaction rate for easier handling during large-pour operation (Smooth-On, Inc. 2016). Foam-iT! 10 Slow, in addition to other products from its supplier, has been used successfully in previous ADR development projects at the lab- and field-scale (Priddy et al. 2010). Therefore, this product was included in the experimental design as the benchmark for comparison in both phases of laboratory experiments (Phase I and Phase II).

Figure 1. Chemical representation of a two-component 1A:1B rigid high density polyurethane.



NCFI Void-Filling System 24-020 is a water-blown urethane foam system designed for void-filling applications that require high foam compressive strength. NCFI Elastomer System 24-077132 is a hydrophobic product designed for rock grout and soil stabilization. HMI RR601 is designed for slab-jacking and infrastructure repair, such as highways, slabs, and heavy-traffic areas.

In addition, three prototype foam formulations were evaluated; two of these formulations were uniquely designed for this project. These products were prepared by HMI Inc. and Primal Innovation (PI) after consistent feedback regarding the experimental results as the project progressed. A modified formulation developed by HMI was designed to provide a slower reaction rate relative to RR601 to prevent product fracture while expanding and curing; a problem encountered during laboratory experiments during Phase I and also during previous ADR field experiments with other products. This material was also formulated to provide a greater compressive strength than RR601. Three small batches of the specially designed HMI product were prepared by the supplier in late 2015 and early 2016 to provide an adequate amount of material to produce specimens for evaluation. Though the same formulation was requested on each occasion, these batches exhibited inconsistent results and, thus, were analyzed separately.

PI Slow is a prototype polymer designed to fill potholes and voided spaces at a slow rate. The slowest-reacting formulation was requested from this supplier to provide an even rise during use and prevent potential operational issues during field use. This product was not specifically formulated for ADR, but is not commercially available. PI Medium was uniquely designed for ADR to produce a faster cure rate relative to the PI Slow formulation to ensure expedient, yet efficient, crater repair during full-scale use. A single batch of this material was analyzed during this project.

2.3 Specimen preparation

Specimens were prepared using slightly different procedures during Phase I and Phase II of this study. A general procedure for specimen preparation is described in this section; specific deviations for each foam material are presented. Procedural variations are included in this report to assert the importance of mixing energy and curing times when producing a satisfactory specimen for evaluation.

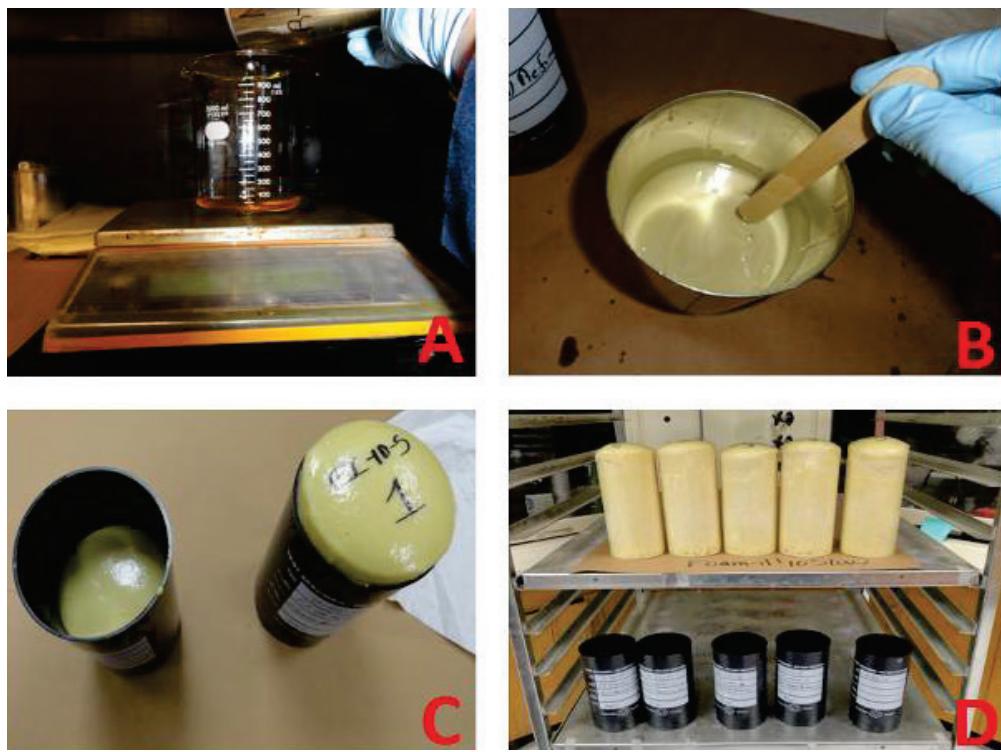
2.3.1 Phase I

Plastic cylinders (4-in.-diam by 8-in.-high) were used to prepare samples of each foam material. A release agent, Stoner Release & Paint™, was applied to the walls, bottoms, and rims of plastic cylinders to ease sample removal process. Both foam components of a particular product were measured in separate glass containers to determine their mass and volume. For each formulation, the components were mixed separately, combined within a 1-qt steel paint can, and stirred based on the respective manufacturer's guidelines for mixing energy and time. The mixed components were immediately poured into a plastic cylinder and allowed to react until the sample was cured. Rise time and tack-free time were determined during this step. Samples were allowed to cure for a pre-determined time before unmolding. General procedures for mixing and molding are shown in Figure 2. Finished samples were weighed and measured to determine mass and volume. Finally, the top dome was removed from each sample and the remaining sample was cut in half to obtain 4-in.-diam by 4-in.-tall UCS test specimens according to ASTM D 1621-04a (2004).

2.3.1.1 *Foam-iT! 10 Slow*

The volume of each component of *Foam-iT! 10 Slow* used during specimen preparation was 150 mL. Mixtures were stirred by hand with a wooden tongue depressor for 1 min. One set of specimens was allowed to react for 1 hr before unmolding, and another set was allowed to cure overnight. Expansion ratio and compressive strength were recorded for both curing times.

Figure 2. Specimen preparation process: A) Measurements of mass and liquid volume, B) Mixing of components, C) Foam curing process, and D) Specimens after unmolding process.



2.3.1.2 NCFI Void-Filling System 24-020

The volume of each component of NCFI Void-Filling System 24-020 used was 200 mL. This volume was required to completely fill the plastic cylinders in which materials reacted. Several alternative mixing procedures were tried before a satisfactory sample was obtained with this foam product. Mixing the two components using the same procedure as that for Foam-iT! 10 Slow proved inadequate, as it produced a heterogeneous sample in which the A component settled toward the bottom of the mixture; this case is shown in Figure 3-A. The mixing was adjusted to follow the manufacturer's guidance, but the resulting sample was soft on the bottom after 1-hr cure time, as shown in Figure 3-B. This mixing procedure was repeated and followed by an 18-hr cure time in which the foam material was left within the molding cylinder; this procedure produced adequate samples for analysis.

Figure 3. NCFI Void-Filling System 24-020 specimens produced using inadequate mixing techniques. A) Profile view of heterogeneous specimens produced using initial procedure. B) Uncured bottom of specimen after premature unmolding.



2.3.1.3 NCFI Elastomer System 24-077132

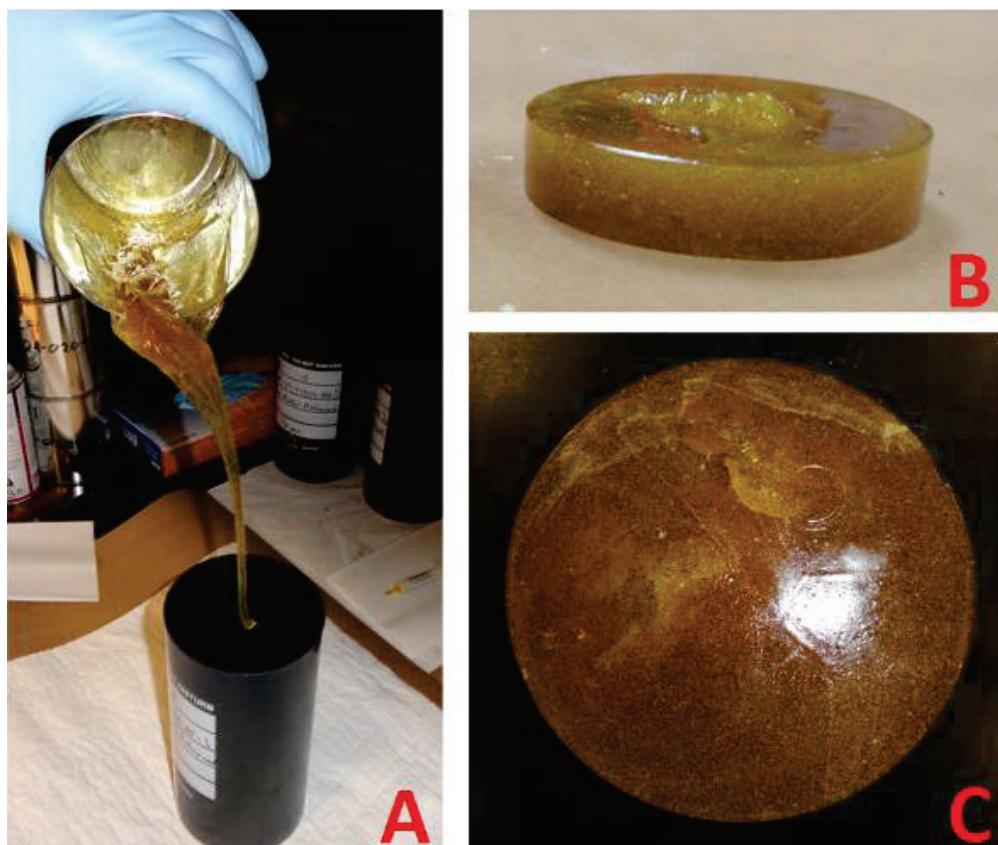
The volume used of Component A and R during NCFI Elastomer System 24-077132 specimen preparation was 150 mL. The “gel time,” or reaction time, specified by the manufacturer was 45 sec. Therefore, the components were hand-mixed using wooden tongue depressors for 40 sec. However, the mixture solidified before it could be fully transferred into a plastic cylinder; the material’s temperature during solidification was 281°F. As shown in Figure 4, the NCFI 24-077132 formulation did not expand. Because expansion is a required characteristic of an ADR foam backfill material, evaluation of this product was discontinued.

2.3.1.4 HMI RR601

Initial mixing procedures for RR601 demonstrated rapid reaction kinetics. Therefore, the mix time was reduced relative to those of the other foam materials. Hand-mixing via wooden tongue depressors for 10 sec provided heterogeneous specimens that contained several voids, as shown in Figure 5. The use of an electric paddle mixer provided heterogeneous specimens that did not fully cure at the bottom of the cylinder, as shown in Figure 6. Another procedure utilized a pneumatic mixer with an axial impeller to agitate the mixture at a high rotational velocity. This procedure was conducted within a molding cylinder to prevent material loss during transfer from steel cans, as observed when preparing previous samples. This process provided samples that contained cracks at the “dome” region at the top of the specimen and a tacky, uncured bottom surface; this case is

displayed in Figure 7. Each of these strategies provided results and input that helped develop the procedure that was ultimately used for HMI RR601 specimen preparation for analysis, which is described next.

Figure 4. NCFI Elastomer System 24-077132 specimen. A) Solidification of material during transfer from can to cylinder. B) Profile view of completed specimen. C) Bottom view of completed specimen.



Ultimately, the HMI RR601 samples that were used for analysis were prepared by agitating the components with high energy in metal cans using a pneumatic mixer with an axial impeller at a high rotational velocity for 8 sec. This procedure allowed proper mix of the components, reduced voids and cracks, and produced more uniform samples. After the components were agitated, the mixed material was immediately transferred to a plastic cylinder. However, because this material reacted quickly, not all of the mixed material could be transferred to the cylinder before solidification and expansion occurred. Regardless, 200 mL of HMI RR601 was used per sample, as this volume was required to fill the 8-in.-tall cylinder after expansion.

Figure 5. HMI RR601 specimens prepared using manual mixing via tongue depressor. A) Profile view of specimens. B) Specimen 1 bottom. C) Specimen 2 bottom. D) Specimen 3 Bottom.



Figure 6. HMI RR601 specimens prepared using electric mixer. A) Tops of specimens within cylinders. B) Bottom of specimen after unmolding.

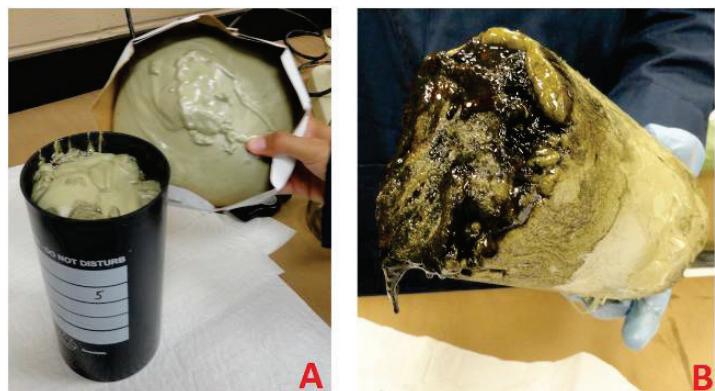


Figure 7. HMI RR601 specimens mixed in plastic cylinders using the air mixer. A) Profile view of specimens before and after unmolding. B) Bottom of specimen following unmolding. C) Crack generated during foam expansion and curing.



2.3.2 Phase II

Specimen preparation during Phase II differed slightly from that of Phase I. Primarily, an effort was made to standardize the procedure among the four products tested during Phase II to prevent bias or error. Therefore, adjustments to the mixing procedure were tested on each formulation for efficacy. Materials were still mixed in 1-qt metal paint cans and transferred to plastic 4 in.-diam by 8-in.-tall plastic cylinders for molding. Throughout the development of the standardized mixing procedure, all materials were combined and mixed using the pneumatic mixer.

2.3.2.1 Component density determination

Densities of individual components for each foam product used in Phase II were calculated and used to determine volumes of individual components when preparing foam specimens for analysis. In preparation for density determination, the components of each foam product were agitated separately within their original containers for two minutes. HMI and Foam-iT! 10 Slow materials were agitated by manually shaking the containers; these materials were supplied in 1-gal plastic containers, as shown in Figures 8-A and 8-B. The PI materials, which were supplied in 1-gal paint cans shown in Figure 8-C, were stirred manually with wooden tongue depressors. Aliquots (100 mL) of components were added to 100 mL

volumetric flasks, and the masses were determined. Table 3 provides material density data. Some error was associated with these density measurements, as air bubbles were observed within materials upon measurement; this effect seemed more apparent in B components. More error was introduced as a small amount of material sometimes spilled over the edge of the flask. Regardless, the liquid density analysis for Foam-iT! 10 Slow provided results that were similar to the manufacturer's guidance of 1:1 (A:B) mix by volume or 100:87 (A:B) mix by mass (Smooth-On, Inc. 2016). A and B components' densities were relatively consistent among the three foam materials tested.

Figure 8. Containers for materials used in Phase II. A) HMI RR601 container. B) Foam-iT! 10 Slow containers. C) PI Slow and PI Medium containers.



Table 3. Foam component liquid densities.

Foam	A Density (lb/ft ³)	B Density (lb/ft ³)	Ratio of Component Mass at 1:1 (A:B) Volume Ratio (A:B)
Foam-iT! 10 Slow	77.0	65.8	100:85.5
Phase II HMI – Batch 1	77.1	68.0	100:88.3
Phase II HMI – Batch 3	76.9	66.9	100:89.1
PI Slow	77.2	67.4	100:87.0
PI Medium	77.1	68.6	100:87.3

* Phase II HMI – Batch 2 was not analyzed for density.

2.3.2.2 Optimal mixing procedure determination

Individual components were mixed using the same mixing procedure as that described for component density determination. Aliquots of 100 to 200 mL of Component B, depending on the foam product, were then collected in steel paint cans, and volumes were determined gravimetrically using the density of each component. The same volume of Component A was added to Component B in the paint can to provide a 1:1 volume ratio between components. A stopwatch timer was started upon initial introduction of components.

Several mixing speeds and times were evaluated to determine the optimal mixing protocol. Materials were first agitated at a mixing rate of 100 to 200 rpm for 60 sec. Foam-iT! 10 Slow produced a relatively uniform specimen with minor voids and heterogeneity (Figure 9-A). PI Slow produced a highly heterogeneous, glassy mixture using this mixing protocol (Figure 9-B). The HMI material expanded rapidly during mixing and, therefore, was not effectively transferred into a cylinder for analysis (-C).

Figure 9. Foam specimens Foam-iT! 10 Slow (A), PI Slow (B), and HMI RR601 (C) produced using low-to-moderate rotational speed via pneumatic mixer with axial impeller.



A second mixing protocol involved agitating the foam product mixtures for 30 sec at the same low-to-moderate mixing rate described previously. This mixing time was recommended by PI. PI Slow again produced a highly heterogeneous, glassy mixture similar to that shown in Figure 9-B. Batch 1 of Phase II HMI material expanded more slowly, but it provided a heterogeneous mixture with large voids and cracks. Figure 10 shows that this HMI material also appeared to display a darker hue relative to the Phase I HMI specimens. Replicate specimens were produced to confirm the results for the HMI and PI foam materials. Foam-iT! 10 Slow samples were not produced using this procedure, because it was inadequate for this foam material.

HMI representatives were contacted to discuss the observed issues, and they suggested using a high mixing rate. Therefore, the third mixing protocol included agitating the mixed components for 30 sec using the air mixer set at a high mixing rate. PI and Foam-iT! 10 Slow materials were homogeneous using this protocol. The HMI material was also homogeneous and displayed a color similar to that observed for the Phase I specimens. Although the mixer's rotational velocity was not recorded and cannot be easily quantified for this operation, the decision was made to use a mixing rate of approximately 5 to 10 times that used initially for Phase II when preparing specimens for the remainder of the project.

Figure 10. Phase II HMI produced via 30 sec of low-to-moderate agitation using pneumatic mixer.



2.3.2.3 Standardized procedure for preparation of specimens

For each formulation, individual components were mixed separately using the procedure discussed previously. A 200-mL aliquot of Component B was collected in a steel paint can. Volume was determined gravimetrically using the density of each component. Then, 200 mL of Component A were added to Component B in a steel can. A stopwatch timer was started upon initial introduction of the components to record the reactivity attributes and other properties. Materials were then mixed for 30 sec at a high mixing rate as discussed previously. The mix was immediately transferred to individual plastic cylinders that had been pre-treated with Stoner Release & Paint™ release agent.

Cured samples remained in the plastic cylinders until analysis was performed. Samples that cured for at least 1 hr were removed from the cylinders with ease. Samples analyzed after shorter curing periods were cut from the cylinder using a box-cutter or similar tool. Full samples were evaluated as necessary for qualitative and quantitative analysis. Then, samples were cut using a Makita miter saw to provide specimens for further analysis. From each full sample, one 4-in. by 4-in. specimen was cut 2 in. from the bottom of the full sample. This section was considered the most homogeneous part of the full sample for use as test specimen based on visual inspection.

2.4 Reactivity

Foam product reactivity was evaluated by measuring the rise time and tack-free time of the material. This test was performed during sample preparation for UCS testing and five replicates were analyzed per product. Rise time was defined as the time from initial component introduction to the time in which the foam appeared to stop expanding or rising. Rise time was determined visually by watching the material and marking the sides of the foam as it rose past the edge of the molding cylinder. Tack-free time was determined via tactile analysis and was defined as the time between initial component introduction and that in which the top surface no longer stuck to a gloved finger.

2.5 Density

Expanded foam density was determined following ASTM D 3574-05 (ASTM 2005) specifications. Prior to cutting specimens for UCS testing, the mass of each full sample was determined, and dimensions of dome and cylinder portions of the samples were measured using a caliper (Starrett® Electronic IP67 Digital Caliper – No. 798B Series). The density of the full sample was determined by dividing the mass of the sample by the measured volume. Once UCS specimens were cut from each sample, mass and volume measurements were taken and density was calculated for each UCS specimen.

2.6 Expansion ratio

Expansion ratio was calculated as a ratio of expanded volume to unexpanded volume. Both full samples and UCS specimens were used to determine this property. Unexpanded volume was measured by adding the volume of each liquid component before mixing. Following curing, any “dome,” or un-level top, created was removed. Volumes of the cylinder and the removed dome were calculated and added to be used to achieve the expanded volume. A minimum of three replicates were required to determine this property.

2.7 Unconfined compressive strength

Five 4-in.-diam by 4-in.-high replicates of each foam material were tested for UCS according to ASTM D 1621-04a (ASTM 2004). During Phase I, samples were cut in half to produce two test specimens (top and bottom) for UCS. In Phase II, only one specimen was cut from the middle of each

sample and used for UCS testing. An Instron unit with a 60,000 lbf capacity load frame, shown in Figure 11, was used for this test. Blue Hill 2.0 and Blue Hill 3.0 software programs were used to support Phases I and II, respectively.

Figure 11. Instron Machine used for compression strength testing.



The objective UCS for each foam material was 300 psi at 2 percent strain. This objective value was selected based on research of cement-stabilized base-course materials that showed a UCS range of 300 to 1,000 psi (Ahlberg and Barenberg 1965). This led to a recommendation that materials with UCS within this range would be considered convenient for base stabilization or replacement. For this project, the threshold, or minimum, UCS at 2 percent strain acceptable for foam backfill materials was 200 psi. The compressive strength at 2 percent strain was the expected amount of maximum strain the foams would receive under loading in the field under a concrete cap (Priddy et al. 2007).

During Phase I, samples were analyzed after 1-hr and overnight cures. Differences in cure time would provide initial data regarding the impact of this variable on UCS. During Phase II, specimens were tested at multiple cure times to determine strength-curing relationships. Specifically, curing times of interest were 15, 30, 45, 60, and 120 min. Adjustments were made to the time increments to accommodate the materials' reactivity criteria, such as the rise and tack-free times. The curing rate would be evaluated by

measuring UCS at each plausible time increment according to ASTM D 1621-04a (ASTM 2004). A minimum of three specimens per foam material were tested.

Times were selected to reflect certain milestones in the expedient ADR process using foam backfill technology. Specifically, the first 15 min of the ADR process consist of crater clean up, cutting, and excavating followed by foam backfill material placement and expansion. Then, a rapid-setting concrete is placed to cap the foam backfill. After 1-2 hr of curing, the repair is functional for aircraft use.

2.8 Hydro-insensitivity

Hydro-insensitivity is defined as the inherent chemical property of a material to be unaffected by water. For this test, 1/2 in., equated to 103 mL, of water was deposited in the bottom of plastic cylinders before foam placement; this volume was based on that used in previous experiments (Priddy et al. 2010). Additionally, this volume was chosen to ensure complete submersion of the foam product in water prior to expansion, as discussed in Geotechnical Test Procedure GTP-8 (NYDOT 2015a). Each sample was prepared using 50 to 100 mL of each component. Samples were visually analyzed during foam expansion for possible reactions or anomalies relative to samples prepared in the absence of water. Rise time and tack-free time were also measured for comparison between samples made with and without water. After foam expansion was complete, samples were extracted from the cylinders for further visual assessment. Each foam product either qualitatively passed or failed the hydro-insensitivity test using the criteria shown in Table 4.

Additionally, samples were analyzed for density and UCS following preparation to further determine success in regards to this property. Results were compared to those of samples prepared in the absence of water, and success would be attained if the sample retained 90 percent of its “dry” density while meeting compressive strength targets, according to Geotechnical Test Procedure GTP-9 (NYDOT 2015b).

Table 4. Pass/fail criteria for foam hydro-insensitivity test.

PASS (Good Cell Structure)*	FAIL (Bad Cell Structure)*
Small/Fine Tight Cells	Large Cells
Minimal Friability	Excessive Friability
Homogeneous Appearance	Heterogeneous Appearance
No Glassiness or Coarse Cell Structure	Glassy Cells
Minimal Striation or Elongation of Cells	Visible Striation or Noticeable Elongation of Cells
Minimal Voiding	Large Voids

* Adapted from Geotechnical Test Procedure GTP-8, New York State Department of Transportation.

2.9 Buoyancy

Buoyancy is the tendency for the finished foam materials to float when immersed in water. This characteristic was determined by subtracting the final foam densities from that of water.

3 Test Results

3.1 Phase I

Table 5 lists a summary of the Phase I test results. NCFI Elastomer System 24-077132 was not included in Table 5, because it failed to expand, failing a major criterion for an alternative ADR product.

Table 5. Summary of Phase I results.

Material	Description	Average Values					
		Rise Time (min:sec)	Tack-free Time (min:sec)	Overall Density (lb/ft ³)	Expansion Ratio	Moisture In-Sensitivity	Compressive Strength at 2% Strain (psi)
Foam-iT! 10 Slow	Overnight cure	12:17	12:17	11.7	5.4	No	240
	Hydro-insensitivity*	12:19	9:40	5.0	12		5
	1 hr cure [†]	10:36	9:43	11.0	5.5		233 top
							205 bottom
NCFI Void- Filling System 24-020	Overnight cure	18:53	20:56	9.7	6.3	No	161
	Hydro-insensitivity*	19:12	19:32	3.9	18.8		10
	1 hr cure [†]	18:50	22:42	10.5	5.9		176 top
							158 bottom
HMI RR601	Overnight cure	2:12	0:32	9.5	7.0	No	119
	Hydro-insensitivity*	2:23	0:30	6.5	11.0		14
	1 hr cure [†]	3:25	0:32	8.2	7.1		102 top
							60 bottom

* 1/2 in. of standing water in the bottom of the cylinder.

† Compression strength was performed on the top and bottom of the specimen.

3.1.1 Visual evaluation

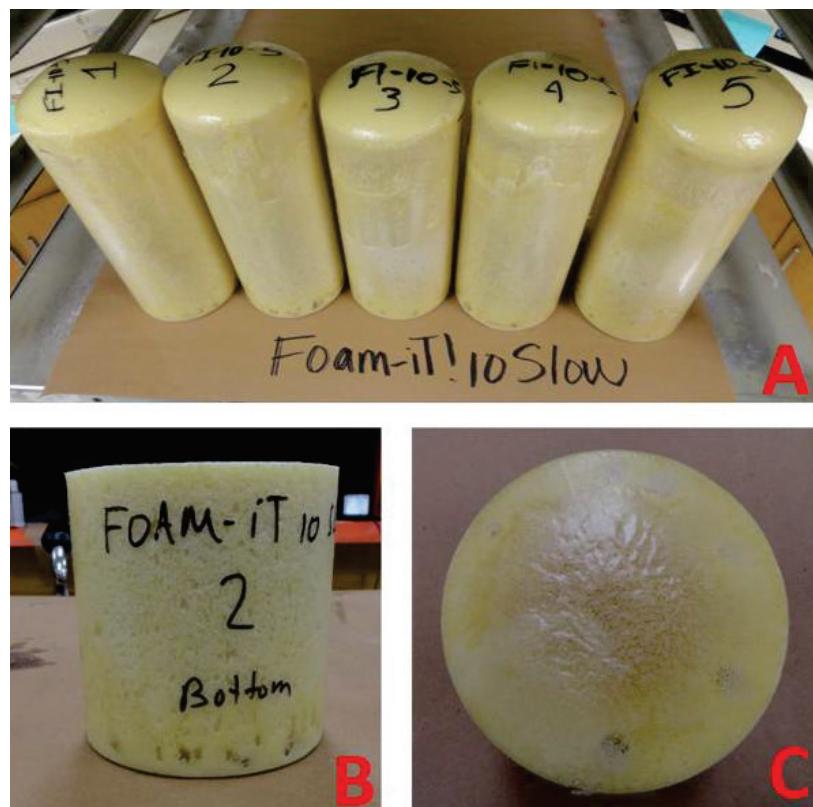
During specimen preparation and production, the specimens were analyzed visually for homogeneity, color, and cell structure. Visual anomalies were evaluated if present.

3.1.1.1 Foam-iT! 10 Slow

The Foam-iT! 10 Slow samples and specimens that were prepared for analysis are shown in Figure 12. These materials displayed a yellow hue that appeared homogenous and contained small cells that seemed

relatively evenly distributed. However, small voids were observed near the bottom of certain specimens, as displayed in Figure 12-B. These voids appeared relatively insignificant but could have introduced error into the data involving UCS, density, and expansion ratio. Otherwise, no significant signs of heterogeneity or potential concerns were observed.

Figure 12. Foam-iT! 10 Slow samples formed in dry plastic cylinders.
A) Full sample after removal from cylinders. B) Specimen prepared for UCS testing. C) Bottom of specimen prepared for UCS testing.



3.1.1.2 NFCI Void-Filling System 24-020

NFCI Void-Filling System 24-020 samples displayed a similar color to that of the Foam-iT! 10 Slow, as shown in Figure 13. This material also displayed homogeneity with small cells seemingly evenly distributed throughout the material. The bottom of the samples were completely cured for the overnight specimens as shown in Figure 13-B. No cracks or visible anomalies were observed.

Figure 13. NCFI Void-Filling System 24-020 samples for analysis. A) Full samples produced using the recommended procedure and cured overnight for analysis. B) Bottoms of overnight-cure samples produced for analysis.



3.1.1.3 HMI RR601

The HMI RR601 material displayed a gray color similar to concrete, as shown in Figure 14. This material featured a much more prominent dome that expanded outward as it rose past the top of the cylinder; the other formulations essentially maintained the cylinder diameter for the area extending above the cylinder. Regardless, the material appeared homogeneous with small cells throughout the majority of the bulk specimens. Some HMI RR601 samples featured cracks at the apex, as shown in Figure 14-B. This formulation also produced small bubble-like voids at the bottom of each sample (Figure 14-C); these voids may have impacted UCS, expansion ratio, and density results. The cause of these anomalies is unknown, but could have been attributed to a rapid cure rate.

3.1.2 Reactivity

HMI RR601 yielded the fastest reactivity with a tack-free time of less than a minute. NCFI Void-Filling System 24-020 had the longest tack-free time of over 20 min, and Foam-iT! 10 Slow was tack-free in an average of 12 min. HMI RR601 consistently became tack-free before it stopped expanding (2 to 3 min.) Foam-iT! 10 Slow became tack-free before it stopped expanding for 1-hr cure and hydro-insensitivity specimens. However, the overnight specimens provided equal rise and tack-free times. NCFI Void-Filling System 24-020 required 2 min after it finished expanding to be tack-free.

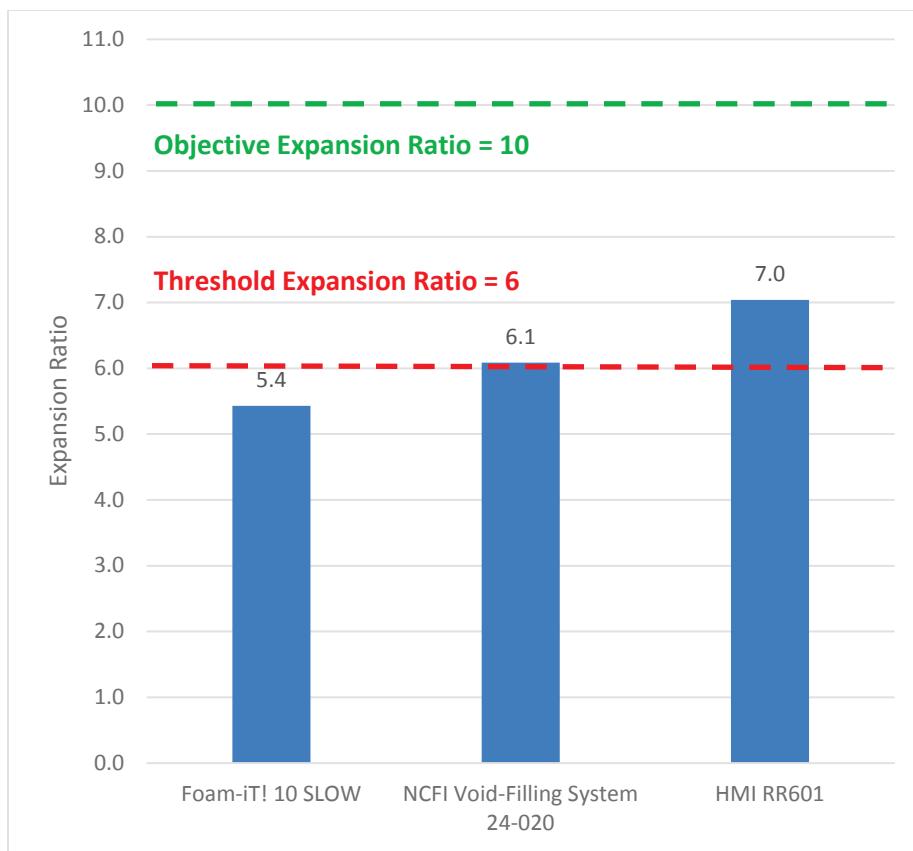
Figure 14. HMI RR601 samples prepared in metal can using an air mixer: A) Sample after unmolding, B) Cut created during the expansion of the foam and C) Bottom of sample after being unmolded.



3.1.3 Expansion ratio

Figure 15 illustrates expansion ratio results for the overnight cure specimens for the three foam products used in Phase I. Two of the three foam products, NCFI Void-Filling System 24-020 and HMI RR601, met the desired expansion ratio of 6-10. Foam-iT! 10 Slow was just under the desired range with an expansion ratio of 5.4.

Figure 15. Average expansion ratio of three products with 1-hr and overnight cures.



3.1.4 Density

Cured density of each foam formulation is shown in Figure 16 and Table 5. Both HMI and NCFI Void-Filling System 24-020 were within the density target range for the overnight specimens; the HMI formulation was within the density target range for the 1-hr-cure specimens, as well. Foam-iT! 10 Slow slightly exceeded the density target range for all materials prepared in a dry cylinder.

Density displayed an inverse relationship with the foam's expansion ratio. As shown in Figure 17, as the expansion ratio increases, the density decreases. This trend is expected, because the foam materials are primarily composed of the same compounds; only minor differences in the formulations are present among the foams. Likewise, densities of individual liquid components should be similar, as portrayed in Table 4. Because the expansion ratio relates the volumes of the cured foam to the initial liquid volume and mass is conserved, expansion ratio directly relates to the density, as well. Errors in measurement prevent an ideal inverse relationship from being observed among the specimen data in terms of these properties.

Figure 16. Phase I foam density data.

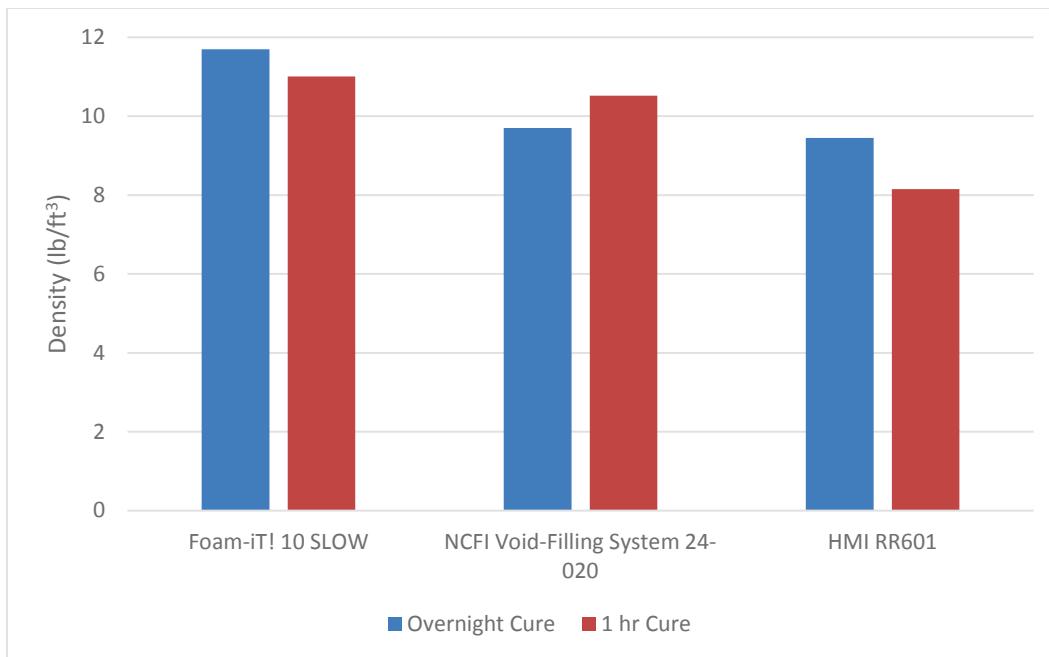
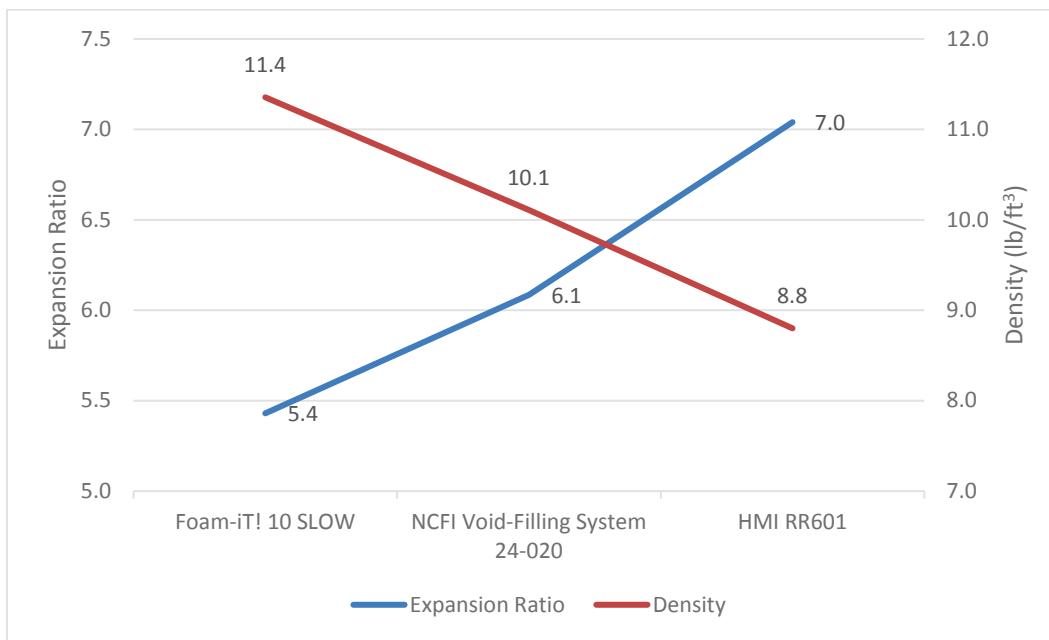


Figure 17. Comparison of Phase I density and expansion ratio data.



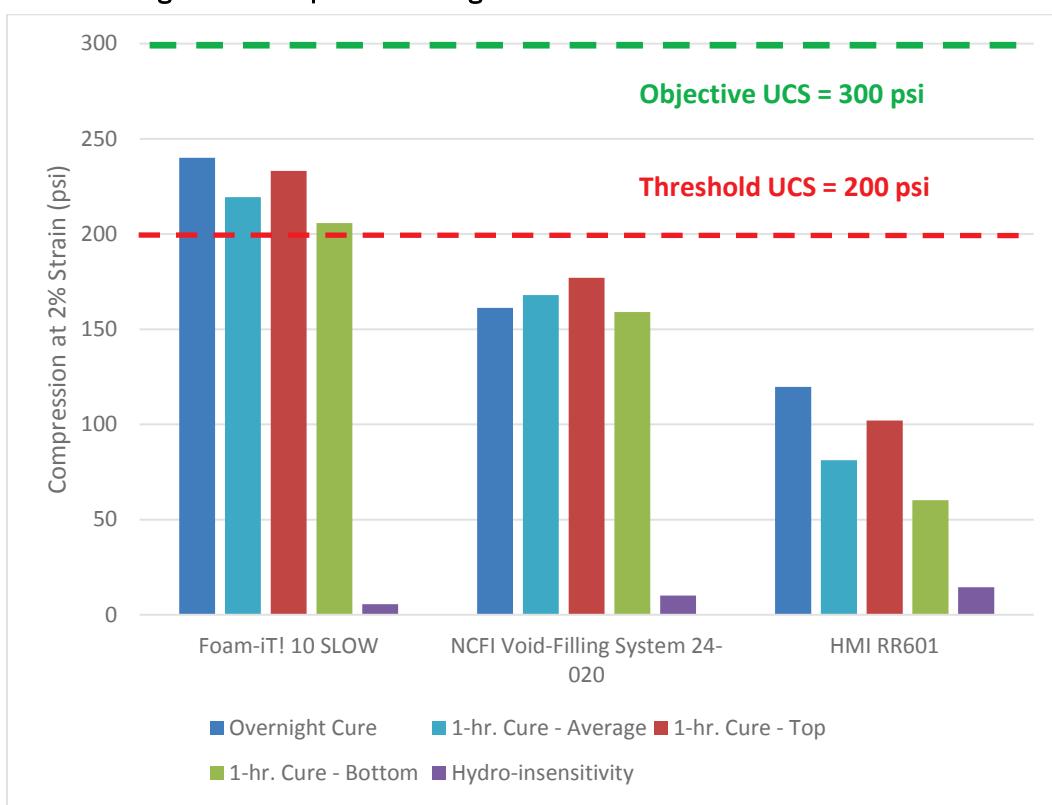
3.1.5 Compressive strength

Because samples were prepared in 4-in.-diam by 8-in.-high plastic cylinders, two UCS test specimens were collected from each mold. For overnight cured materials, a combination of specimens from the top 4 in. and bottom 4 in. of the molded samples were analyzed; the exact

combination for each product was not recorded. However, for the 1-hr cure specimens, the “top” and “bottom” samples were segregated and tested separately to determine any discrepancy regarding sample location.

Foam-iT! 10-SLOW had the highest average UCS among the specimens, as illustrated in Figure 18. This was the only foam product tested that met the threshold compressive strength to be considered as a backfill material for expedient ADR. This threshold was met after only 1 hr of curing. UCS data for Foam-iT! 10 Slow that was cured overnight was greater than that for the 1-hr cure specimens. This data could indicate that the specimens had not fully cured within 1 hr. Also, a slight difference of approximately 12 percent was observed between the top and bottom specimens when tested after 1 hr of curing.

Figure 18. Compressive strength results for three Phase I formulations.



Observations regarding differences in compressive strength based on cure time and specimen location were also made for the HMI specimens. The HMI RR601 showed a difference of more than 40 psi between the “top” and “bottom” samples. The cause of this difference is unknown.

The NCFI Void-Filling System 24-020 showed a different trend regarding compressive strength and cure time. This formulation showed a slightly greater UCS value in the 1-hr specimens relative to those that cured overnight. Additionally, a small deficit of approximately 10 percent was observed for the specimens tested at the bottom of the mold relative to those that were tested from the top. Regardless, this formulation did not meet threshold strength requirements for any cure time or specimen location, as indicated previously.

The differences in UCS for the 1-hr and overnight specimens could have been associated with variation in density in addition to the cure time. Overnight Foam-iT! 10 Slow and HMI RR601 specimens both had higher densities and higher UCS than their 1-hr counterparts. Conversely, for NCFI Void-Filling System 24-020, the 1-hr cure specimens had higher densities and UCS. A relationship between these two properties could be present.

Stress-strain curves associated with these specimens are shown in Appendix A. The maximum compressive stress for each specimen is included in Appendix B.

3.1.6 Hydro-insensitivity

Each product tested for hydro-insensitivity experienced an increase in expansion and a significant decrease in compressive strength and density, as shown in Table 6, relative to overnight specimens prepared in the absence of water. These data indicate failure in terms of hydro-insensitivity according to NYDOT GTP-9, as 90 percent of the final density associated with specimens produced in the absence of water was not retained (NYDOT 2015b). Regardless, each specimen failed the GTP-8 testing protocol for hydro-insensitivity for various reasons. Ultimately, these data show that no Phase I products are hydro-insensitive and, thus, should not be in direct contact with appreciable quantities of water during preparation and use.

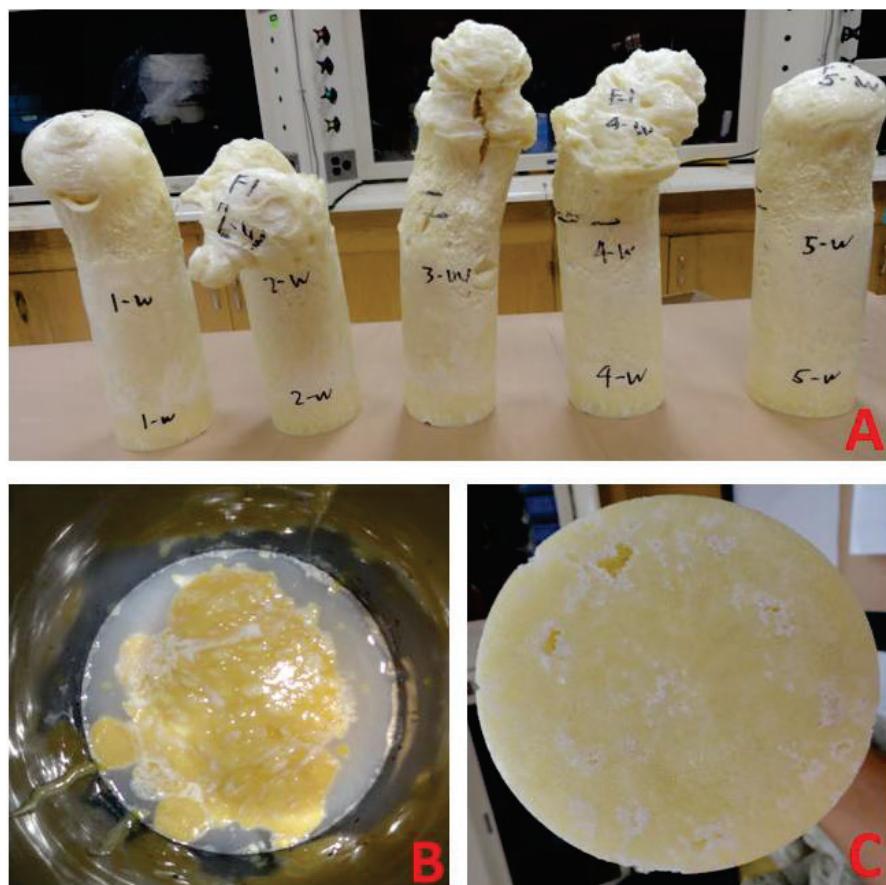
Table 6. Reduction in physical properties for hydro-insensitivity specimens relative to the overnight specimens prepared without water.

Formulation	Expansion Ratio Change (%)	UCS Change (%)	Density Change (%)
Foam-iT! 10 Slow	126	-98	-57
NCFI Void-Filling System 24-020	199	-94	-60
HMI RR601	57	-88	-31

3.1.6.1 Foam-iT! 10 Slow

Figure 19 illustrates Foam-iT! 10 Slow produced with water and 100 mL of each Component Added to the plastic cylinders. Because the density of the liquid foam mixture was greater than that of water, the liquid foam was fully submerged prior to expansion. While curing and expanding, specimens started bending when they passed the top of the plastic cylinders, generating cracks along their sides. Water spilled from cylinders as specimens expanded, leaving almost no water in the bottom of cylinders when reaction completed. Specimens produced with water had more than twice the expansion ratio compared to specimens produced in dry cylinders. Rise times and tack-free times of specimens produced with water were similar to the values of specimens prepared in dry cylinders. However, wet specimens were soft and contained a thin layer filled with voids at the base. Wet specimens decreased to 5.02 lb/ft³. Compressive strength reduced by approximately 98 percent.

Figure 19. Foam-iT! 10 Slow specimens formed with water present in the plastic cylinders. A) Full specimens after removal from cylinders. B) Specimen expanding within water in cylinder. C) Bottom of Specimen 1-W.

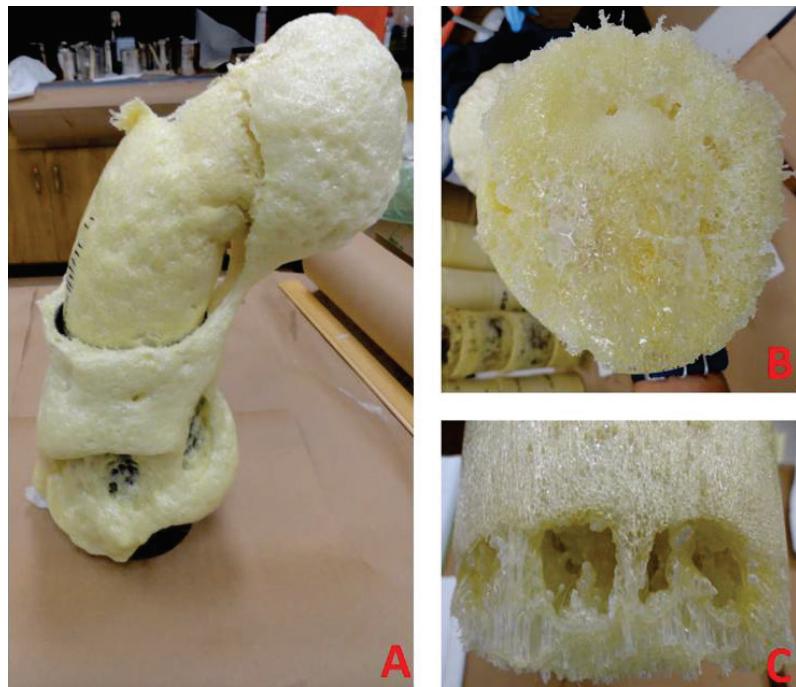


Overall, Foam-iT! 10 Slow failed the hydro-insensitivity testing protocol according to GTP-8 because much larger cells were produced for these specimens relative to those made in dry cylinders. Additionally, a thin layer of voids were produced at the bottom of specimens, as shown in Figure 19C. Both of these attributes are specifically listed in Table 4 as failure criteria for this test.

3.1.6.2 NCFI Void-Filling System 24-020

Prior to evaluation, specimens produced in the absence of water were reviewed for comparison. The hydro-insensitivity test procedure for this product was similar to that listed above except 50 mL of each component was used; 1/2 in. of water was still added to each cylinder. A smaller volume of each component was required as initial tests showed a greater expansion of the foam material associated with the water compared to other materials. Almost 100 percent of the water remained in the bottom of the plastic cylinder after specimen extraction, and large voids were visible in the bottom of specimens (Figure 20B-C). Additionally, much larger cells were produced for these specimens relative to those made with dry cylinders. Therefore, this product is not considered hydro-insensitive according to GTP-8.

Figure 20. NCFI 24-020 Specimens. A) First specimen before unmolding, B) Bottom of another specimen and C) Bottom of the first specimen.



Rise time and tack-free time results were similar to specimens made with dry cylinders. However, the average specimen density was 3.71 lb/ft³, which corresponds to an expansion ratio of approximately 19 in comparison to the initial liquid density. In addition, the average UCS was reduced by approximately 94 percent compared to specimens produced in dry cylinders.

3.1.6.3 HMI RR601

Figure 14 illustrates specimens of this product prepared in dry cylinders, and Figure 21 shows specimens produced in cylinders containing 1/2 in. of water. Large voids were visible in the bottom of specimens produced in wet cylinders, and cracks were noted throughout the specimens. Therefore, this product failed hydro-insensitivity testing according to Table 4. Rise time and tack-free time results of wet specimens were similar to the specimens made in dry cylinders. The average density of wet specimens was 6.53 lb/ft³, which was significantly lower than that of specimens produced in dry cylinders (9.7 lb/ft³). Thus, this product failed the hydro-insensitivity test according to GTP 9. Additionally, the average final volume of these specimens was 11 times that of the original liquid mixture. Lastly, the average compressive strength was 14 psi, a reduction of approximately 88 percent compared to specimens produced in dry cylinders.

Figure 21. HMI RR601 specimens prepared with 1/2 in. of water in the bottom of the cylinder: A) Specimens after being unmolded and B) Bottom of the specimens.



3.1.7 Buoyancy

Buoyancy data for the products are shown in Table 7. All of the specimens, regardless of cure time or inclusion of water, would float when exposed to water, as the density of each specimen was less than that of water (62.4 lb/ft³).

Table 7. Phase I buoyancy data.

Formulation	Buoyancy (lb/ft ³)		
	Overnight Cure	1 hr Cure	Hydro-insensitivity
Foam-iT! 10 Slow	50.7	51.4	57.4
NCFI Void-Filling System 24-020	52.7	519	58.5
HMI RR601	53.0	54.2	55.9

3.2 Phase II

Experimental results for Phase II are listed in Table 8. The target values for each parameter are included for comparison.

Table 8. Experimental results for Phase II.

	Cure time (min)	Replicates	Compressive strength at 2% strain (psi)	Rise time* (min)	Set Time* (min)	Expansion Ratio*	Density (lb/ft ³)
Objective value	30	-	300	5-30	5-30	10	-
Threshold value	60	-	200	5-30	5-30	6	-
Foam-iT! 10 Slow	20	5	36	9.6	12.8	5.8	12.4
	30	5	121				
	45	5	176				
	60	5	239				
	120	5	277				
	18+ hr	5	321				
Phase II HMI (Batch 1)	15	3	3	2.8	3.4	7.0	10.5
	30	3	27				
	45	3	--				
	60	3	--				
	120	3	--				
	18+ hr	5	268				
Phase II HMI (Batch 2)	18+ hr	5	284	3.0	3.3	7.0	10.5

Phase II HMI (Batch 3)	15	3	1	8.3	7.3	7.9	9.2
	30	3	6				
	45	3	28				
	60	3	58				
	120	3	160				
	18+ hr	5	203				
PI Slow	60	3	38	31.4	52	6.2	11.7
	120	3	233				
	18+ hr	5	316				
PI Medium	15	3	22	9.8	11.2	6.4	11.3
	30	3	145				
	45	3	184				
	60	3	217				
	120	3	310				
	18+ hr	5	321				

*Based on 18+ hr specimens alone.

3.2.1 Visual evaluation

Each specimen produced for analysis during Phase II of this project displayed a homogeneous appearance. No significant anomalies were observed.

Specimens that were produced for Phase II are shown in Figure 22. These specimens featured the same appearance as those analyzed in Phase I of this project. These specimens produced for analysis were significantly more homogeneous than the specimens produced using a low mixing rate, as shown in Figure 23.

Each of the specimens produced for the Phase II HMI formulation displayed a uniform gray appearance, as featured in Figure 24. Specimens displayed the same appearance regardless of batch analyzed. Several specimens fractured slightly as they rose above the tops of cylinders. This fracture was caused by friction between the foam and the edge of the cylinder. Although this fracture is not an inherent property of the foam caused by excessive heat or rapid curing, it shows a lack of strength in the foam at this stage of the curing process. Fracture of this nature may be expected during use of this material in the field.

Figure 22. Foam-iT! SLOW specimens produced during Phase II.



Figure 23. Visual comparison of pneumatically mixed Foam-iT! SLOW specimens produced using two preparation methods.

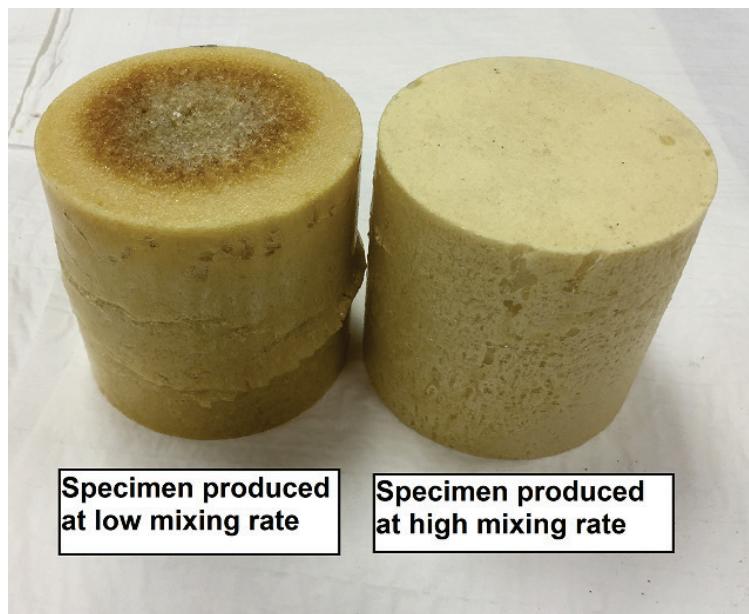


Figure 24. Phase II HMI Batch 1 specimens.



The PI formulations PI Slow and PI Medium displayed nearly identical appearances, as shown in Figure 25. The formulation PI Slow displayed a darker yellow hue relative to the PI Medium, but both formulations displayed a similar yellow color to the Foam-iT! 10 Slow material. Both formulations also displayed small voids near the bottom of specimens, as shown in Figure 26. These voids may reduce the compressive strength of the overall specimen.

Figure 25. PI specimens. A) PI Slow. B) PI Medium.



3.2.2 Reactivity

The target range for reactivity criteria, including rise time and tack-free time, was 5 to 30 min. This target range was established to help determine the applicability of the material when used in the field. A low rise time and tack-free time indicates potential operational concerns for the materials during their intended use. Clogging and backflow may occur as a result of expansion and solidification within the dispensing equipment during use or

shortly after use. Contrarily, a slow reactivity, determined from high rise or tack-free times, may cause delays in use as the cure rate may not sufficiently accommodate the anticipated schedules during pavement repair.

Figure 26. Bottom of PI Medium specimen displaying small voids. These voids were observed on several specimens regardless of formulation.



Of the four products tested during Phase II, only Foam-iT! 10 Slow and PI Medium met the target reactivity times. Foam-iT! 10 Slow had an average rise time of 9.6 min and an average tack-free time of 12.8 min, both well within the 5 to 30 min desired range. These properties were consistent with those of the Foam-iT! 10 Slow specimens that were prepared during Phase I of the project; the rise and tack-free times of the Phase I specimens were both approximately 10 to 12 min, respectively, as discussed previously. PI Medium had similar rise and tack-free times of approximately 10 min and 11 min, respectively. The difference in reactivity between the Foam-iT! SLOW and PI Medium was not significant.

However, the PI Slow formulation reacted too slowly; the rise time and tack-free time were 31.4 min and 52 min, respectively. These results create potential concerns for delay during full-scale use for pavement repair, depending on the application method.

Each of the three HMI batches that were supplied for Phase II reacted differently. The first batch, which was delivered to ERDC in December 2015, reacted relatively quickly with rise and tack-free times of 2.8 min and 3.4 min, respectively. This material seemed to expand quickly after a short delay of approximately 30 sec after transfer to the cylinder; this material was prepared using the same procedures as the other materials. The second batch was supplied in February 2016 and reacted more quickly than the first batch. Although this material had similar rise and tack-free times, the reaction initiated approximately 15 sec after the specimens were introduced. The initiation of the reaction was indicated by a color change, i.e., the mixture displayed a much darker hue, and a significant release of heat. The third batch, which arrived at ERDC in March 2016, reacted much more slowly than the previous two specimens. This material began to expand about 3.5 min after initial introduction and fully expanded and cured after approximately 10 min and 11 min, respectively; these criteria were within the target ranges specified for reactivity.

Two major concerns were raised regarding the Phase II HMI formulation. First, the rapid cure rates observed in the first two batches indicate potential backflow concerns during operation for pavement repair. Second, significant variability observed between batches indicates insufficient consistency that could adversely affect operations during large batch pours. The supplier stated that the reactivity variation was likely caused by the small quantities of the latter two batches; seemingly only 5 gal of these materials were prepared upon request. The first batch was subsampled from a larger batch in which a full-scale demonstration was performed using this material. Despite the rapid cure rates identified by the measurement criteria, the Phase II HMI formulation felt soft to the touch for a substantial time after becoming tack-free. This property was not observed for the other two materials tested in Phase II.

3.2.3 Expansion ratio

The HMI materials had the highest expansion ratios of the Phase II materials. Each batch achieved the threshold of 6 with an expansion ratio exceeding 6.5. Because of the increased expansion ratio, only approximately 160 mL of each component of this material was used when preparing each specimen; additional material was not necessary to fill plastic cylinders. Reduction of material did not appear to cause issues during molding and analysis. PI Medium achieved the second-highest expansion ratio of 6.4, which was within the target range specified for this project. PI Slow also

achieved the target with an expansion ratio of 6.2. However, Foam-iT! 10 Slow had an expansion ratio of 5.8, which was slightly lower than the range targeted for this property. This expansion ratio was similar to that observed in Phase I, which was 5.4 to 5.5; the observed difference was likely a result of error or typical variation associated with the product.

3.2.4 Density

As stated previously, materials producing the highest expansion ratio would have the lowest density, considering that liquid densities were similar. Thus, the Phase II HMI specimens had the lowest densities. PI specimens had similar densities of 11.3 to 11.7 lb/ft³. Foam-iT! 10 Slow had a density of 12.4 lb/ft³, which was similar to that observed for this material during Phase I.

3.2.5 Compressive strength

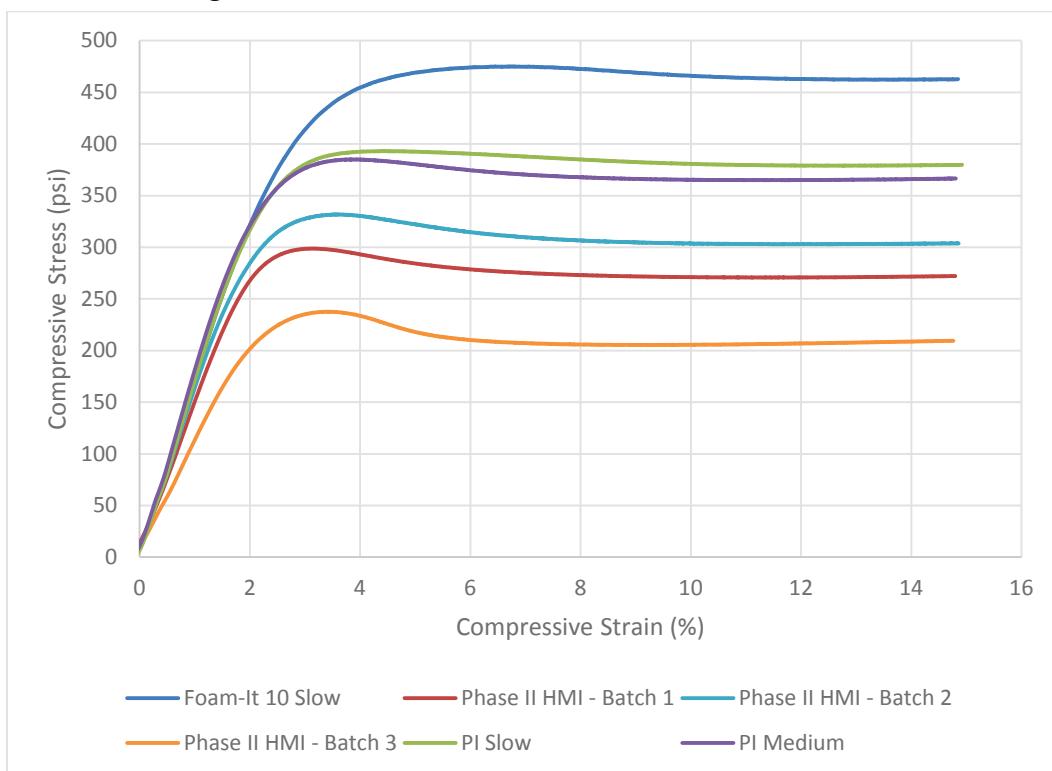
Of the products tested in Phase II, Foam-iT! 10 Slow and both PI materials exceeded the target UCS of 300 psi after curing overnight, as shown in Table 6 and Figure 27. Variation in UCS among these three formulations is minimal and could be associated with experimental error or typical specimen variation. Considering that the manufacturers' suggestion for full curing is 4 hr, the UCS of any of the formulations analyzed is not expected to increase beyond these values.

No Phase II HMI specimens met the compressive strength target at 2 percent strain after an overnight cure. However, these specimens did surpass the threshold compressive strength of 200 psi. Considering that the third batch had an average compressive strength of 203 psi, variation among the specimens if used in future development efforts must be minimized to ensure that UCS does not decrease below the threshold during use.

The analytical method for these specimens was developed to produce compressive strength beyond 2 percent strain; the maximum strain targeted for these specimens was 15 percent. These additional data were produced to determine the maximum compressive stress and the impact of higher loads on the foam materials. Figure 27 shows the compressive stress data at these higher strain values. Ultimately, Foam-iT! 10 Slow produced the highest maximum compressive stress at 475 psi. PI Slow and PI Medium produced essentially identical maximum compressive stresses of 393 psi and 385 psi, respectively. Only the second batch provided of

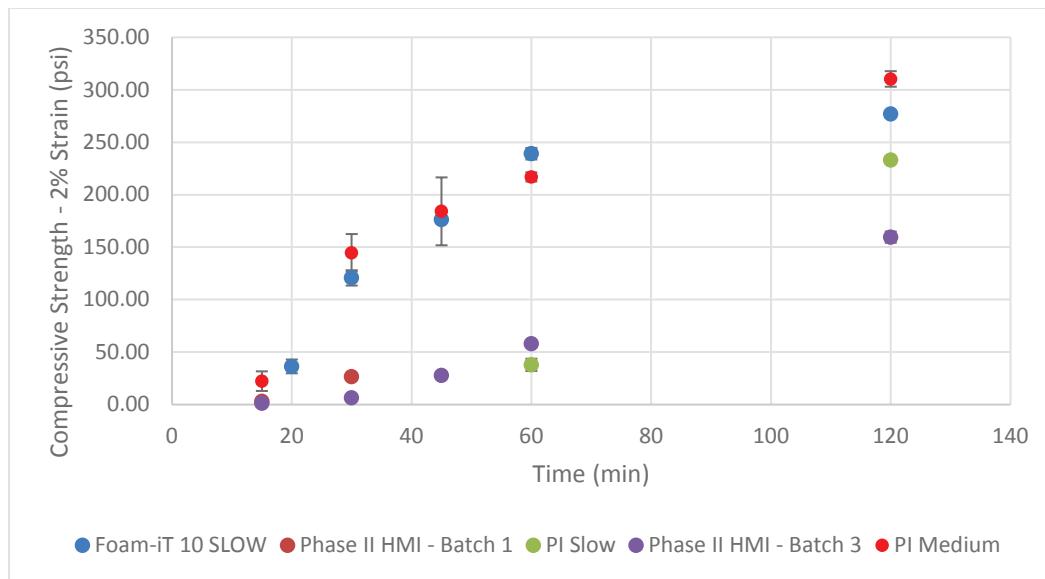
Phase II HMI produced a maximum compressive strength exceeding the target; this material had a maximum compressive strength of 332 psi. Each formulation exhibited the same trend in compressive stress after the maximum stress was attained for the overnight specimens; the stress slightly decreased upon reaching the maximum stress but ultimately remained constant as the strain increased. More data are included for overnight compressive strength in Appendices A and B.

Figure 27. Stress-strain curves for Phase II foam formulations.



Compressive strength of each product increased considerably with cure time, as shown in Figure 28. These data indicate that, although the foam products have fully expanded and set by their observed rise and tack-free times, they have not fully cured. This phenomenon was particularly noticeable for each of the Phase II HMI formulations. For these materials, finished specimens felt considerably soft and compressible to the touch for approximately 20 min after the product had fully expanded and become tack-free. This issue, which is indicated by the HMI products' very low compressive strength data in Figure 28, was not observed for the other materials analyzed during this study.

Figure 28. UCS versus cure time.



Foam-iT! 10 Slow and the PI specimens felt hard and rigid to the touch as they became tack-free. However, Foam-iT! 10 Slow and PI Slow exhibited another issue during this study, as the bottoms of these products were still significantly tacky upon removal for the lowest measured time increment. This tack was likely caused by a lack of exposure to air. The individual specimens were stored in the molding cylinders until approximately 5 min before analysis. Therefore, the bottoms of the specimens would not be exposed to the environment, and moisture would not easily evaporate. Specimens were cut into 4-in. by 4-in. cylinders approximately 2 min prior to compressive strength testing; the tacky portions of the specimens were removed to prevent any impact on the analysis. Immediately after cutting, the interior of each product tested in this study was soft and compressible to the touch at lower cure times. This observation further asserts that the material cures more readily when exposed to air.

The storage, removal, cutting, and testing processes were standardized among the specimens to prevent bias. The standardized process was developed to minimize exposure to air. Because the foam will be used to fill craters that will only allow the top of the foam to be exposed to air, this process provided the best representation of full-scale use.

Overall, PI Medium and Foam-iT! 10 Slow specimens reached the threshold compressive strength of 200 psi within 1 hr of curing. PI Medium material reached the target compressive strength of 300 psi after another hour of curing. PI Slow also reached the 200-psi threshold after

2 hr of curing; this specimen was analyzed only at cure times of 60 min and 120 min because its reactivity did not allow for a tack-free product to be produced earlier in the curing process. Phase II HMI specimens did not reach the 200-psi threshold for compressive strength within 120 min of curing. Only Batch 3 of this material was analyzed at each cure time. The Batch 1 supply depleted during these tests, and Batch 2 was excluded from these tests based on its reactivity concerns previously noted. Regardless, Phase II HMI is not recommended for expedient ADR, as the product will not carry sufficient strength to withstand the proposed loads at the rate proposed for the project. More data regarding the kinetic compressive strength study are available in Appendices A and B.

3.2.6 Hydro-insensitivity

Qualitative data for the Phase II specimens undergoing hydro-insensitivity testing are shown in Table 9. Quantitative data, including density and UCS, for these specimens is shown in Table 10. The comparison of the hydro-insensitivity data to data of the specimens made in the absence of water is shown in Table 11. No specimens analyzed in Phase II were deemed hydro-insensitive based on NYDOT's GTP-8 and GTP-9.

Table 9. Failure criteria for foam formulations based on GTP-8.

Formulation	Failure criteria
Foam-iT! 10 Slow	Glassy cells, excessive voids
Phase II HMI	Striations, heterogeneity, excessive voids
PI Slow	Excessive friability, large cells, excessive voids
PI Medium	Large cells, excessive voids

Table 10. Quantitative hydro-insensitivity data for Phase II foam formulations.

	Minimum Compressive Strength at 2% strain (psi)	Rise Time (min)	Tack-free Time (min)	Minimum Expansion Ratio	Density (lb/ft ³)
Objective	300	5-30	5-30	10	--
Threshold	200	--	--	6	--
Foam-It 10 Slow	14.69	14.94	14.13	20.91	3.41
Phase II HMI (Batch 3)	27.91	13.65	25.05	14.04	5.19
PI Slow	13.05	13.00	25.55	18.01	4.09
PI Medium	20.01	10.00	9.13	21.41	3.42

Table 11. Percent change on hydro-insensitivity specimens relative to the standard specimens produced in the absence of water.

Product	Compressive Strength (%)	Density (%)	Expansion Ratio (%)
Foam-iT! 10 Slow	-95.43	-72.45	263.26
Phase II HMI (Batch 3)	-89.59	-50.61	101.78
PI Slow	-95.88	-64.96	192.86
PI Medium	-92.96	-68.32	221.74

Each foam formulation produced similar specimens when undergoing hydro-insensitivity analysis. Qualitatively, each specimen exhibited poor cell structure. The specific anomalies for these specimens are shown in Table 9. Additionally, each specimen contained several internal voids that are shown in Figure 29. These voids were not observed in the interior of the “dry” specimens that were produced in the absence of water. Each specimen increased significantly in expansion ratio causing a large decrease in density. The specimens also exhibited a large decrease in compressive strength. This decrease was likely caused by decreased density, presence of voids, and poor cell structure.

Figure 29. Interior of hydro-insensitivity specimen.



Figure 30 displays the hydro-insensitivity specimens. The PI formulations both featured bottoms that were not uniform, as shown in Figure 31. This issue was also present in one of the Phase II HMI specimens that was produced. This lack of uniformity was caused by the bottom fracturing and separating from the molding cylinder. This issue caused additional concern, because this material may readily separate when used from the base and float atop potential standing water within the crater. Additional figures displaying the anomalies observed during the hydro-insensitivity analysis are shown in Appendix C.

Figure 30. Hydro-insensitivity samples: A) Foam-iT! 10 Slow, B) Phase II HMI, C) PI Slow, and D) PI Medium.

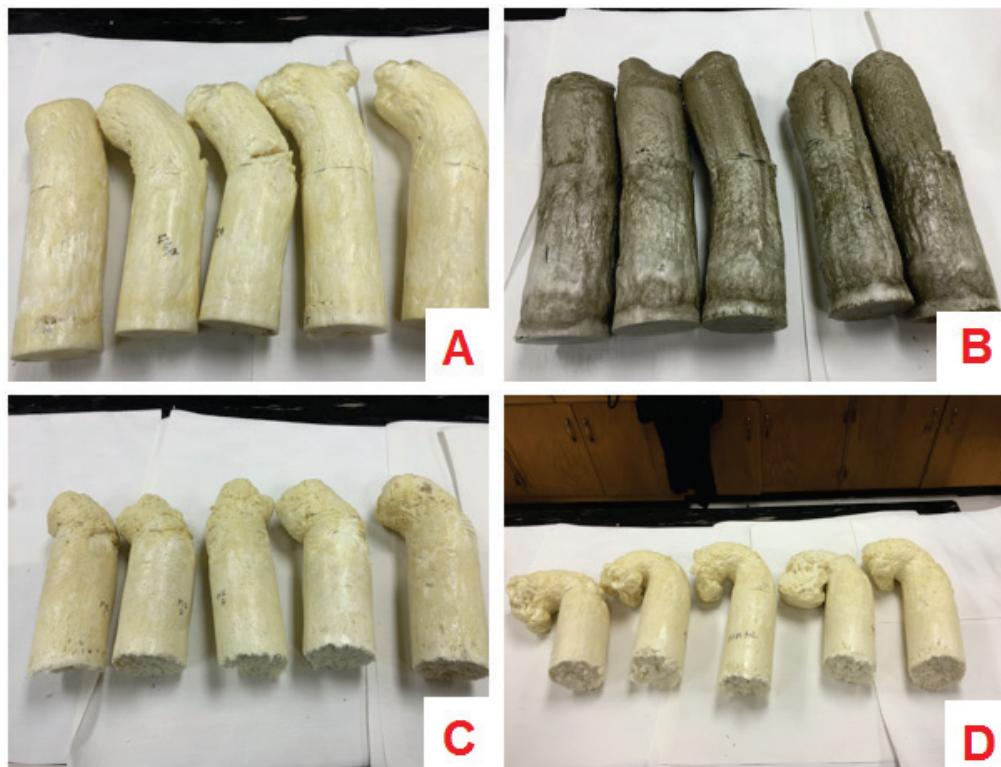


Figure 31. Bottom of PI Slow hydro-insensitivity specimen.



3.2.7 Buoyancy

Buoyancy data for Phase II are shown in Table 12. As with Phase I, the specimens analyzed during this phase of analysis would all float in environments containing excess water.

Table 12. Phase II buoyancy data.

Product	Density - Uniform (lb/ft ³)
Foam-It 10 Slow	50.0
Phase II HMI (Batch 1)	51.9
Phase II HMI (Batch 2)	51.6
Phase II HMI (Batch 3)	53.2
PI Slow	50.7
PI Medium	51.1

4 Discussion of Results

The criteria for analysis of these materials involved a tiered approach to determine the appropriate recommendation for material(s) for field testing. This hierarchy includes the following criteria in order of significance:

1. Compressive strength
2. Reactivity (rise and tack-free time)
3. Expansion ratio
4. Cost
5. Hydro-insensitivity.

The only materials to meet the compressive strength targets were Foam-iT! 10 Slow, PI Slow, and PI Medium. The Phase II HMI specimens met the threshold of minimum compressive strength value as well. The other materials tested in this study did not meet the compressive strength requirement and, therefore, will not be recommended for use in field exercises or operation.

Of the specimens that met the compressive strength criteria, only Foam-iT! 10 Slow and PI Medium consistently displayed adequate reactivity for expedient ADR timelines. These materials both had a rise time of approximately 10 min and tack-free times of 10 to 15 min. Reactivity of this rate should prevent clogging of essential machine parts during pumping or similar operations for dispensing materials in field scenarios. Materials with faster reaction rates, indicated by shorter rise and tack-free times, may expand or solidify more quickly upon mixing and cause backflow in these dispensers. The HMI specimens would potentially cause this concern, if the material is not effectively removed from the dispenser quickly after it is fed. Additionally, the Phase II HMI formulation exhibited much variation in regards to reactivity. This variation was apparently associated with the batch sizes requested. Such inconsistency provides minimal security and assurance for uniformity among batches when requested for full-scale use. PI Slow has a slow reactivity, indicated by a rise time of approximately 30 min and a tack-free time of 50 to 60 min. Thus, ADR efforts would likely be delayed, as the operating crew would be required to wait until the material cured before continuing with the capping process. Considering the

necessity of speed regarding ADR efforts, this material would not be acceptable for use in the field.

In terms of expansion ratio, the PI Medium expanded the most of the formulations that successfully met the strength and reactivity criteria. This material produced an expansion ratio within the range targeted for this project. Foam-iT! 10 Slow produced a slightly lower expansion ratio of 5.3 to 5.7. This deficit compared to that of the PI Medium is not considered significant. However, the increased expansion ratio translates to a lower required quantity of foam material necessary to accomplish the overall mission of the project. Therefore, logistical costs in terms of transport and storage would be reduced. This factor ultimately supports the goal of the customer to further become “Lighter and Leaner” in terms of crater backfill and repair. However, the Foam-iT! 10 Slow still accomplishes these goals relative to the current ADR mechanism of compacted soil or aggregate or the proposed ADR backfill of flowable fill. Other formulations tested during this study produced similar results in terms of expansion ratio; the HMI formulations exhibited the greatest expansion ratio of 7 to 8. However, these materials did not meet the criteria for other critical properties.

The cost of each formulation analyzed in this study has not yet been determined for the quantities anticipated for future development efforts and utilization. PI Medium was specially formulated for this study, as discussed previously. No cost has yet been assigned to this material or disclosed to ERDC. Foam-iT! 10 Slow is commercially available, as previously discussed. However, the price for substantially large quantities has not been disclosed to ERDC. None of the prices for the other materials that were evaluated in this study have been disclosed, either. However, once these prices are disclosed, they will be considered when determining the appropriate path forward for full-scale utilization.

None of the materials evaluated were deemed hydro-insensitive. Therefore, this characteristic should not be considered when selecting a material for future development. Instead, efforts conducted in the field should be performed in which a hydrophobic barrier is utilized to prevent the intrusion of water into the foam mixture. Other means of repelling water or transporting water away from the void space to be filled should be used as necessary.

The technical data for all of the materials in relation to the performance metrics are summarized in Table 13. This table includes the materials tested for both phases of the study.

Table 13. Summary of technical data for foam formulations.

	Minimum Compressive Strength at 2% strain (psi)	Rise Time (min)	Tack-free Time (min)	Hydro-Insensitivity	Expansion Ratio	Density (lb/ft ³)
Objective	300	5-15	5-15	---	10	---
Threshold	200	5-30	5-30	---	6	---
PI Medium	321.1	9.8	11.2	Failed	6.4	11.3
Foam-iT! 10 Slow	321.5	9.6	12.8	Failed	5.8	12.4
PI Slow	316.4	31.4	52.0	Failed	6.1	11.7
Phase II HMI; Batch 1	268.1	2.8	3.4	Failed	7.0	10.5
Phase II HMI; Batch 2	284.3	3.0	3.3	Failed	6.7	10.8
Phase II HMI; Batch 3	202.5	8.3	7.3	Failed	7.9	9.2
HMI RR601	119.7	2.2	0.5	Failed	7.0	9.5
NCFI Void-Filling System 24-020	161.2	18.9	22.7	Failed	6.3	9.7
NCFI Elastomer System 24-077132	Not evaluated; did not expand					
Key	Met Criteria		Marginal		Did not meet criteria	

5 Conclusions and Recommendations

Ultimately, two materials were deemed suitable for future development efforts regarding the foam backfill ADR project. One material is currently commercially available. The other material was uniquely designed to support the needs of ERDC and its customers.

Foam-iT! 10 Slow is a commercially available rigid foam material that successfully met the criteria for this project in terms of strength and reactivity. This material provided compressive strengths of over 300 psi at 2 percent strain once it fully cured. This material fully expanded in roughly 10 min and became tack-free in approximately 13 min. The expansion ratio for this material was 5.8, which was approximately the threshold for this study. This material has been used in previous ADR efforts conducted by ERDC and was included in this project as the benchmark material based on its previously demonstrated performance. The study's results showed not only did the Foam-iT! 10 Slow continue to provide the same performance that it did in previous experiments, but also one other formulation is capable of delivering equivalent or better results.

PI Medium was specifically developed to meet the criteria for this project, which includes a compressive strength exceeding 300 psi at 2 percent strain while expanding more than six times its liquid volume and setting within a 10- to 15-min window. This material was adjusted from a previous formulation in which the reactivity produced results between 30 and 60 min.

The primary recommendation for development efforts in regards to this project is to conduct field tests and other scale-up experimentation. Overall, this project was successful in that it provided the basis for two potential options for foam backfill material. Both of these materials should be included in the field exercises to further evaluate their performance. Depending on the outcome of these future tests, the two options can then be further evaluated in terms of material cost, logistical burden, and supply to determine the appropriate actions for full-scale use.

The next step in regards to formulation development is to improve the hydro-sensitivity of the foam products. None of the products tested in this

study were deemed hydro-insensitive according to the test methods used. The contingent action to immediately address this issue would be to prevent contact between the foam and excessive moisture through the use of impermeable barriers and other methods. However, improvements to the formulations that successfully met the other criteria analyzed in this study would provide the greatest protection against moisture concerns.

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Appendix A: Stress-strain Curves

This section features the stress-strain curves that were produced by the Bluehill software during compression testing via ASTM D 1621-04a for plastics compression testing. Curves for specimens from both phases of the project are included.

A.1 Phase I stress-strain curves

Figures A1 through A3 display stress-strain curves for Phase I of the project. Only the specimens that curved overnight in the absence of water are included. The cause of variation observed for HMI RR601 was not determined and could be associated with error in preparation.

Figure A1. Phase I Foam-iT! 10 Slow overnight cure (dry) stress-strain curve.

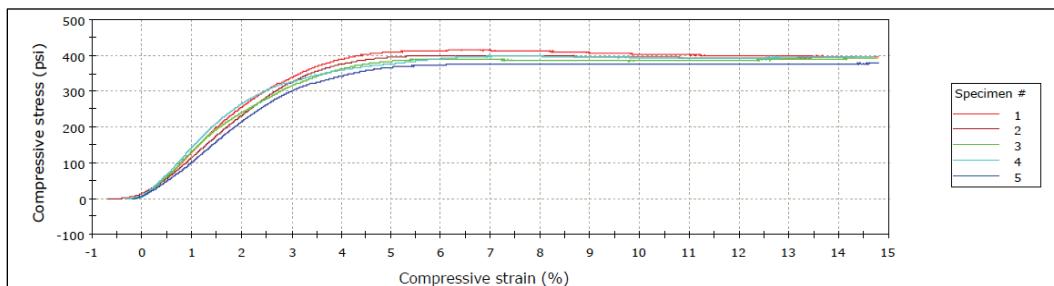


Figure A2. NCFI Void-Filling System 24-020 overnight cure (dry) stress-strain curve.

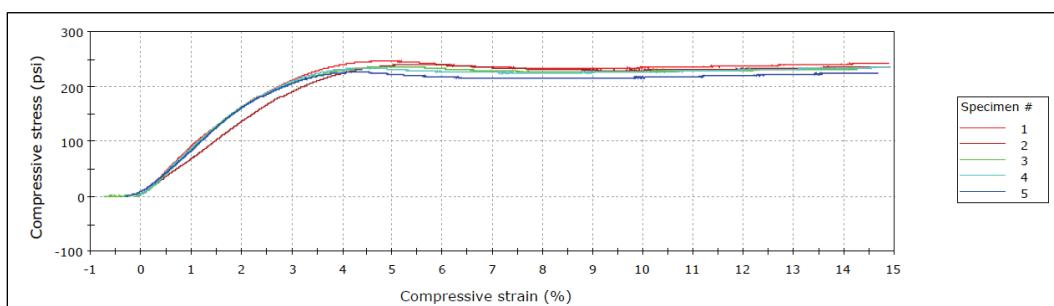
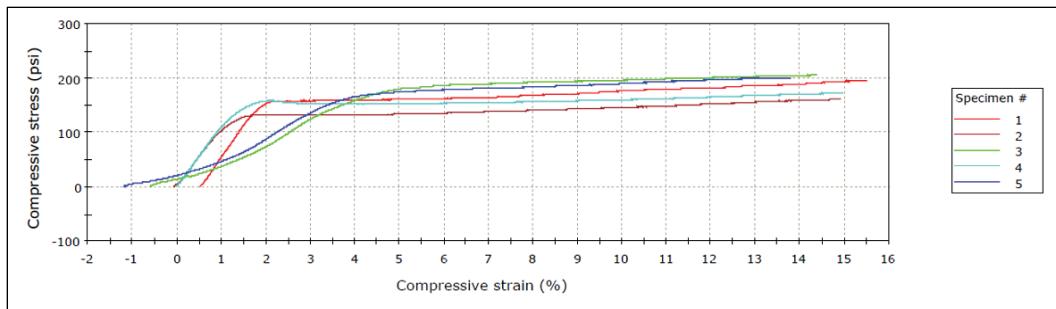


Figure A3. HMI RR601 overnight cure (dry) stress-strain curve.



A.2 Phase II specimens

This section includes the stress-strain curves for Phase II of the experiments. Curves generated at each cure time are shown in addition to those for the hydro-insensitivity specimens.

A.2.1 Phase II overnight specimens

Figures A4 through A9 display stress-strain curves for Phase II of the project. Only three specimens of Phase II HMI: Batch 2 were analyzed. Five specimens were analyzed for each of the other materials.

Figure A4. Phase II Foam-iTi! 10 Slow overnight cure (dry) stress-strain curve.

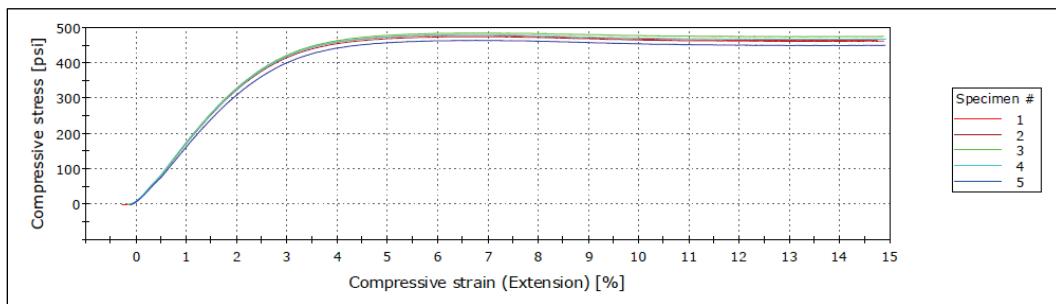


Figure A5. Phase II HMI Batch 1 overnight cure (dry) stress-strain curve.

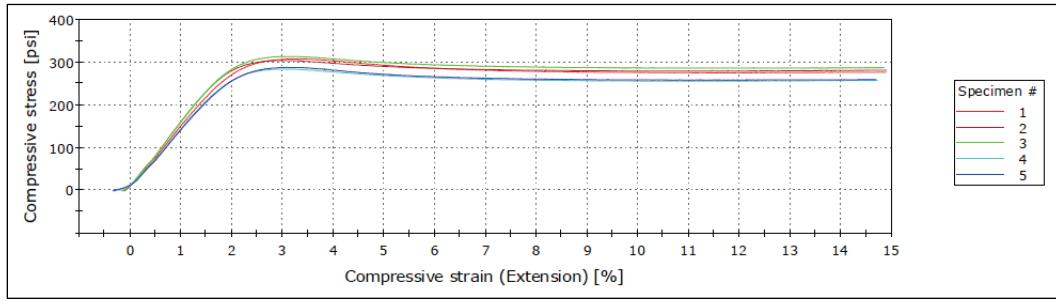


Figure A6. Phase II HMI Batch 2 overnight cure (dry) stress-strain curve.

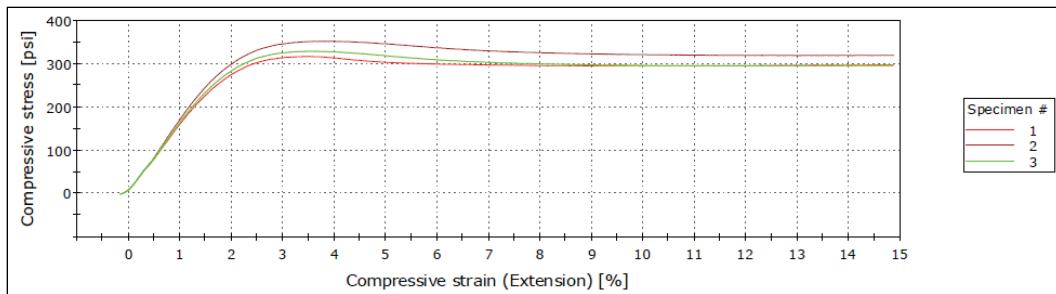


Figure A7. Phase II HMI Batch 3 overnight cure (dry) stress-strain curve.

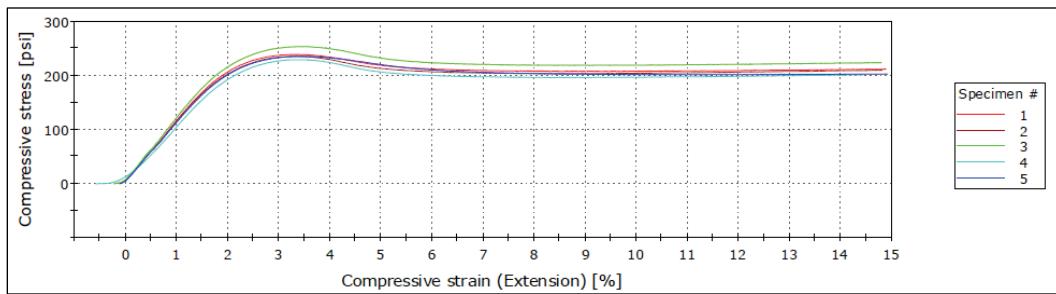


Figure A8. PI Slow overnight cure (dry) stress-strain curve.

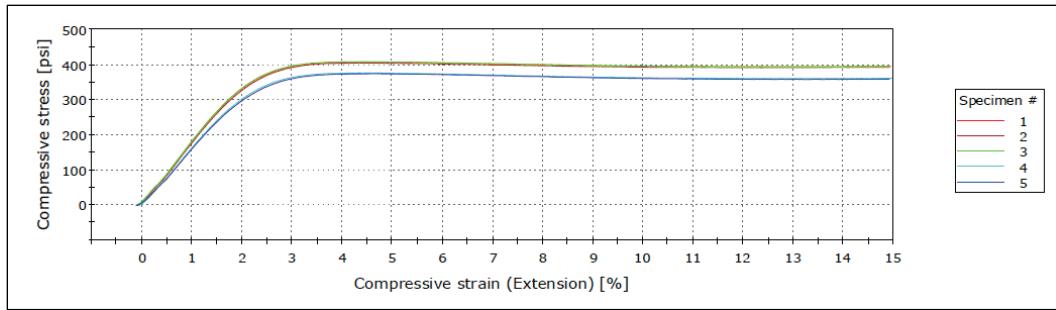
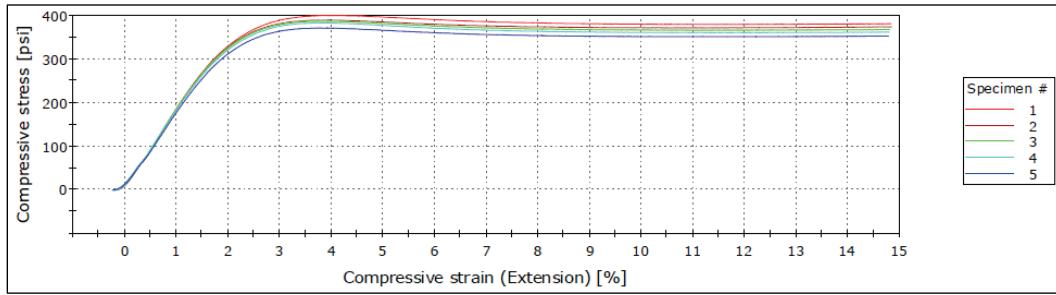


Figure A9. PI Slow overnight cure (dry) stress-strain curve.



A.2.2 Phase II time study specimens

Figures A10 through A28 display the stress-strain curves for the UCS test produced for different cure times during Phase II of the experimentation. Figures A10 through A14 display the curves for Foam-iT! 10 Slow.

Figures A15 through A16 display the curves for the first batch of the HMI formulation tested during Phase II; the curves for the third batch of this material are shown in Figures A17 through A21. The stress strain curves for P Slow and PI Medium are shown in Figures A22 through 23 and A24 through A28, respectively.

Figure A10. Phase II Foam-iT! 10 Slow 15-min. cure stress-strain curve.

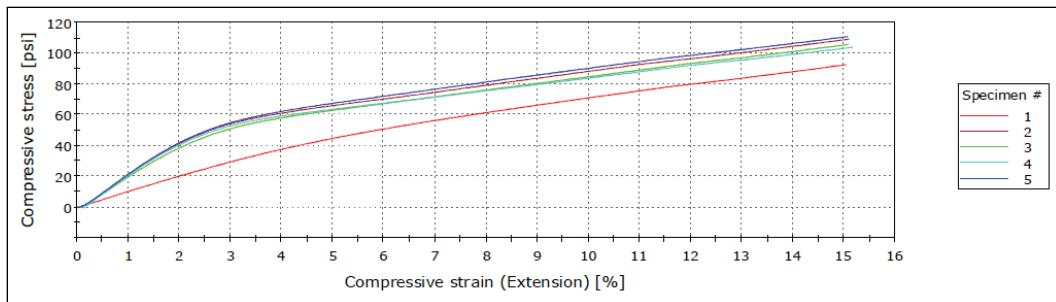


Figure A11. Phase II Foam-iT! 10 Slow 30-min. cure stress-strain curve.

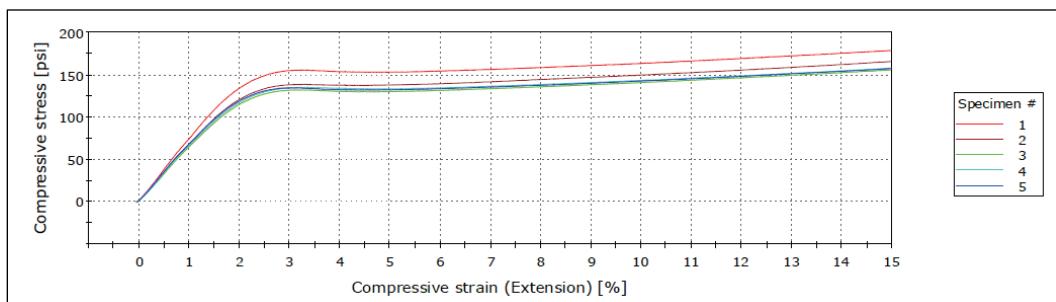


Figure A12. Phase II Foam-iT! 10 Slow 45-min. cure stress-strain curve.

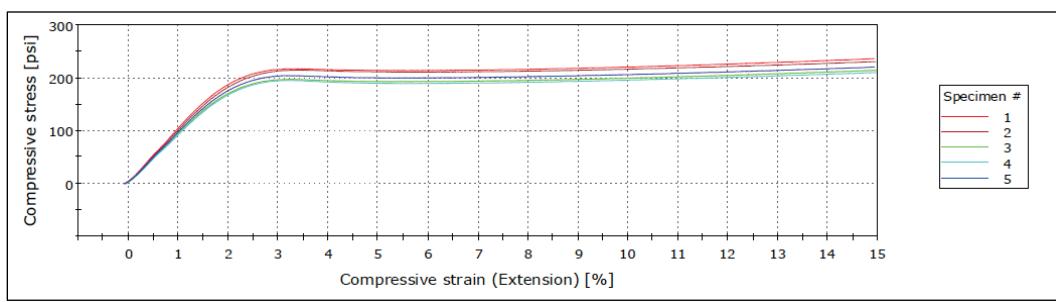


Figure A13. Phase II Foam-iT! 10 Slow 60-min. cure stress-strain curve.

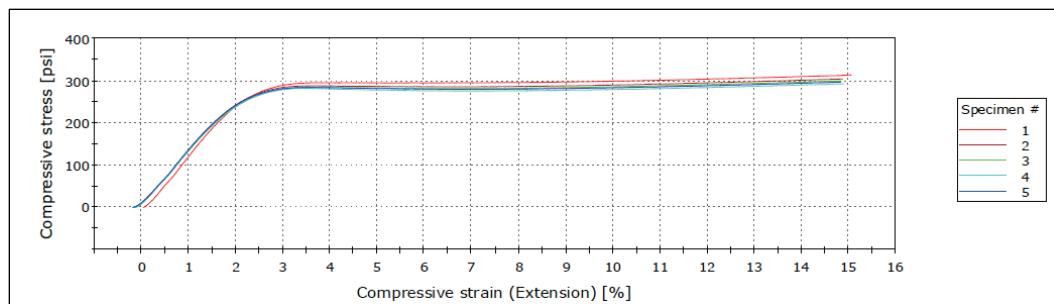


Figure A14. Phase II Foam-iT! 10 Slow 120-min. cure stress-strain curve.

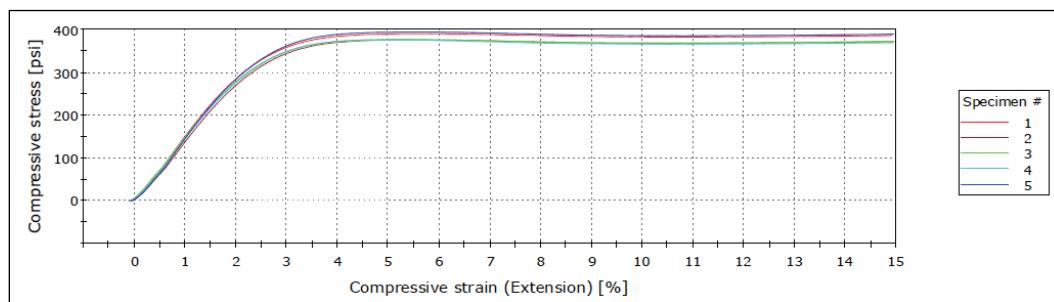


Figure A15. Phase II HMI Batch 1 15-min. cure stress-strain curve.

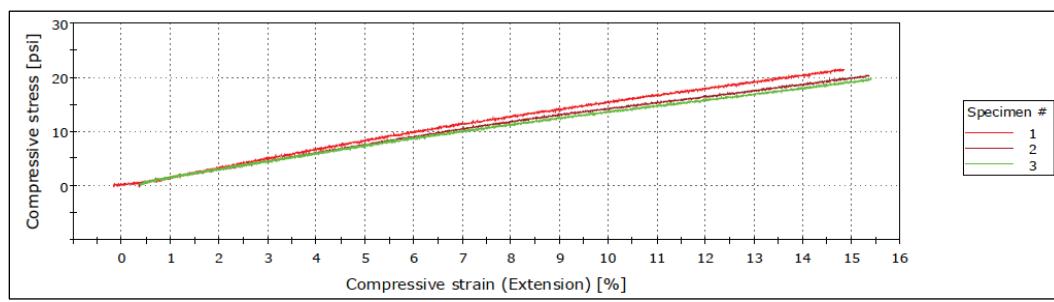


Figure A16. Phase II HMI Batch 1 30-min. cure stress-strain curve.

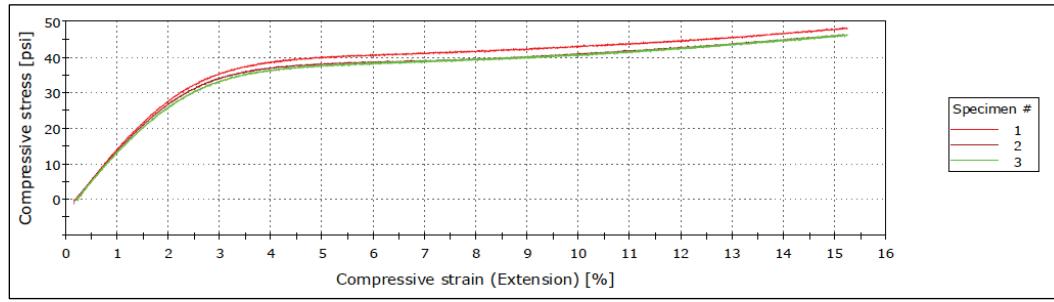


Figure A17. Phase II HMI Batch 3 15-min. cure stress-strain curve.

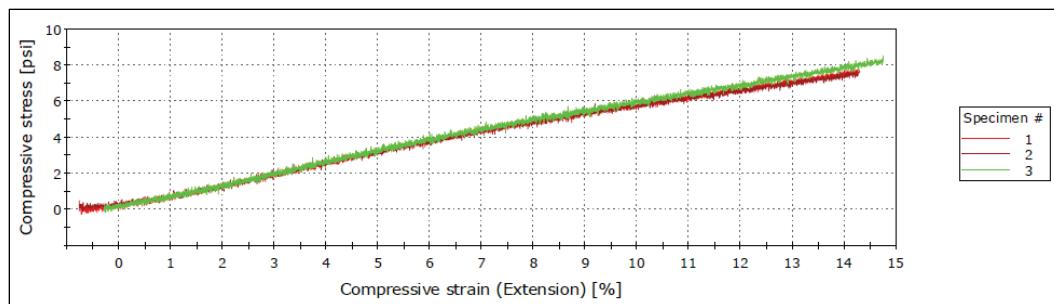


Figure A18. Phase II HMI Batch 3 30-min. cure stress-strain curve.

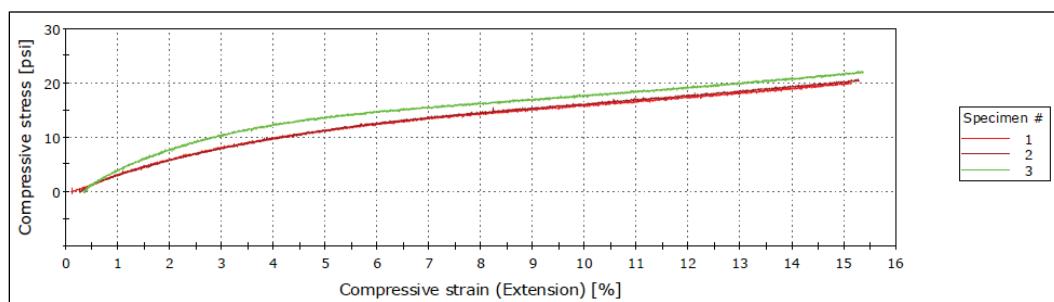


Figure A19. Phase II HMI Batch 3 45-min. cure stress-strain curve.

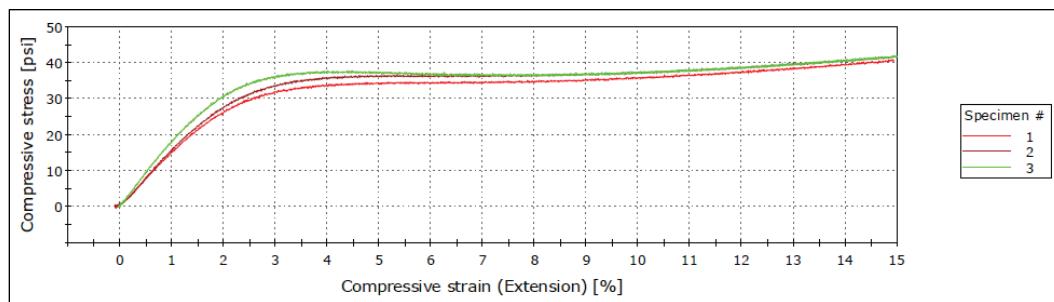


Figure A20. Phase II HMI Batch 3 60-min. cure stress-strain curve.

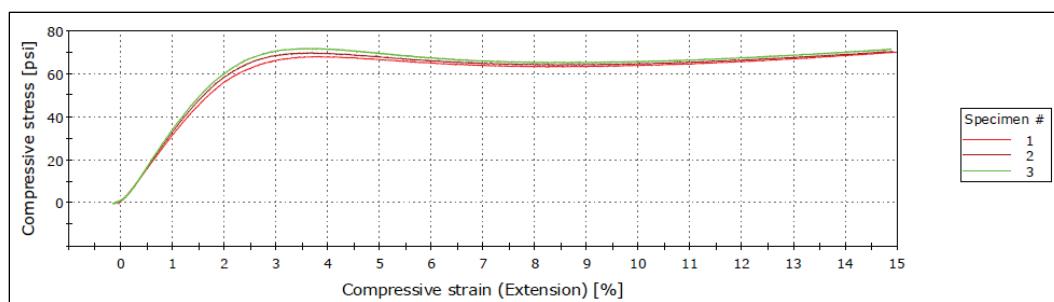


Figure A21. Phase II HMI Batch 3 120-min. cure stress-strain curve.

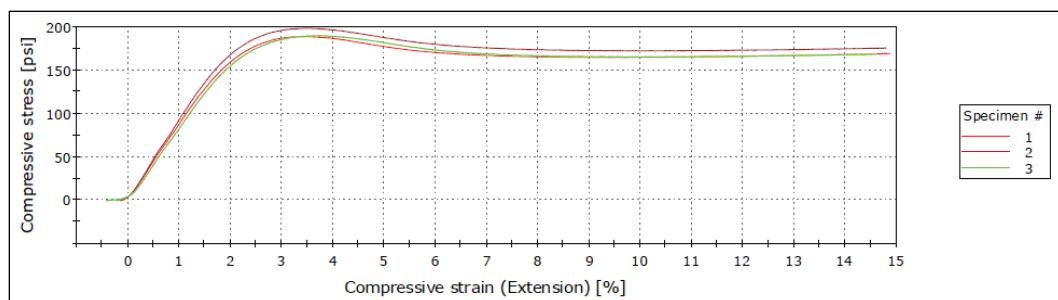


Figure A22. PI Slow 60-min. cure stress-strain curve.

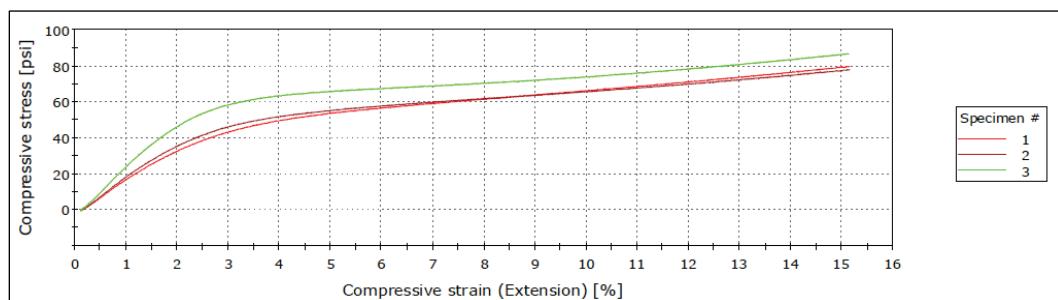


Figure A23. PI Slow 120-min. cure stress-strain curve.

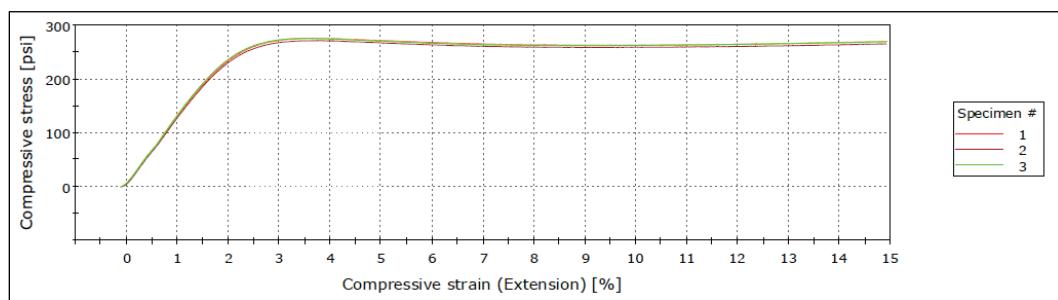


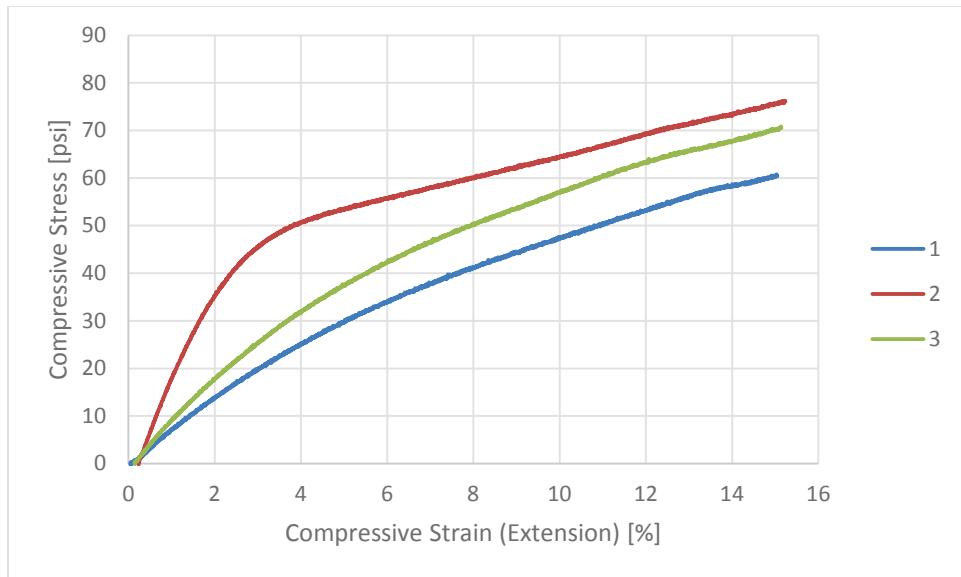
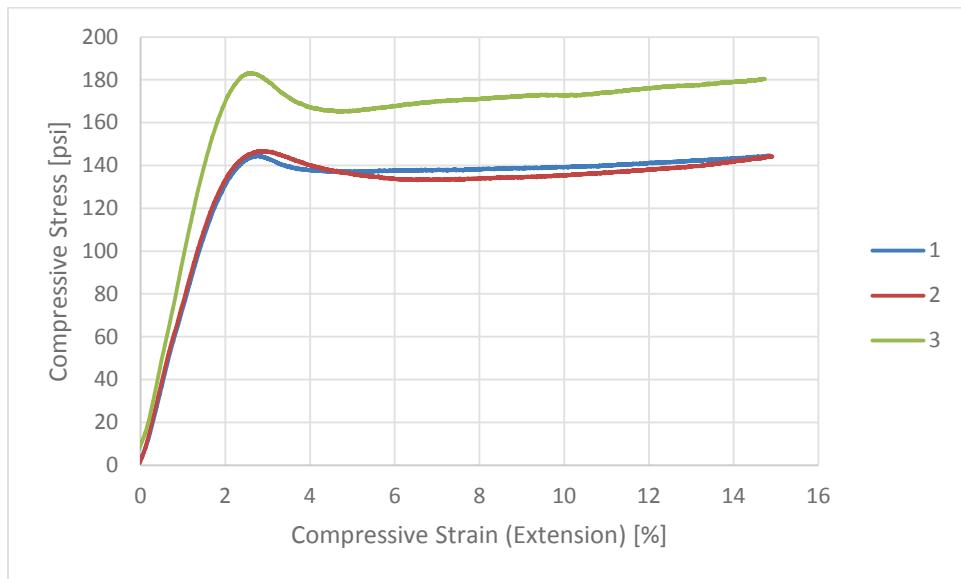
Figure A24. PI Medium 15-min. cure stress-strain curve.**Figure A25. PI Medium 30-min. cure stress-strain curve.**

Figure A26. PI Medium 45-min. cure stress-strain curve.

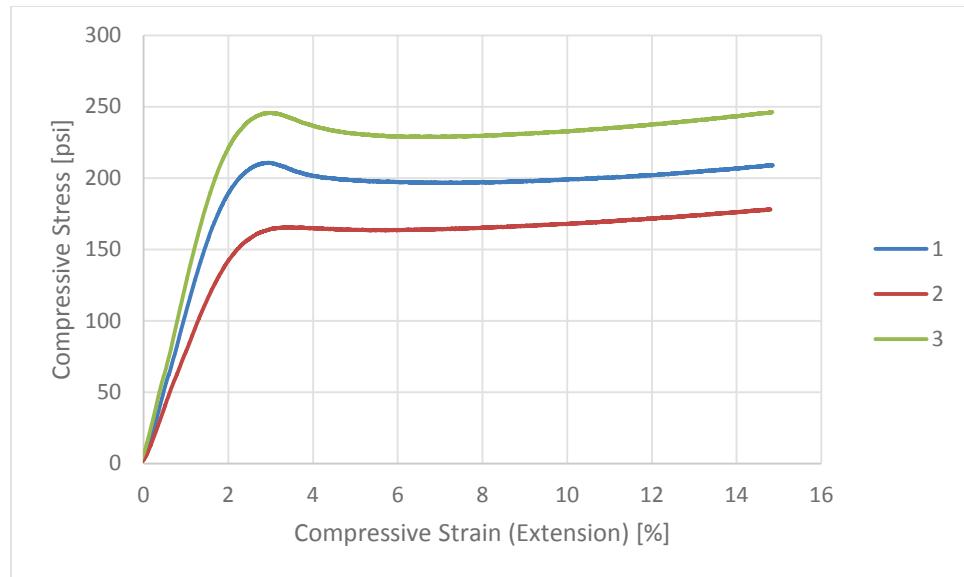


Figure A27. PI Medium 60-min. cure stress-strain curve.

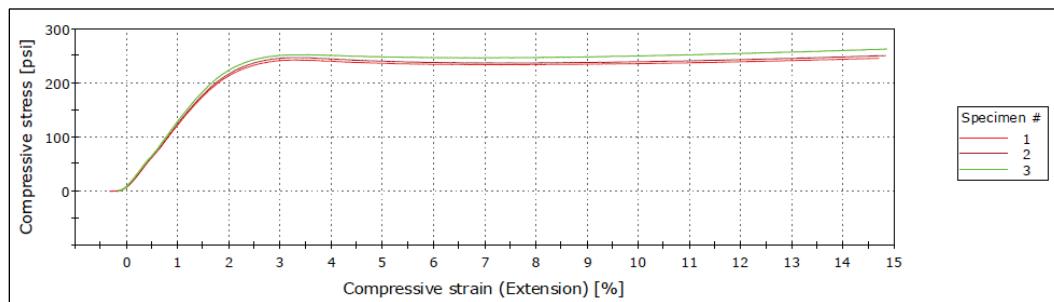
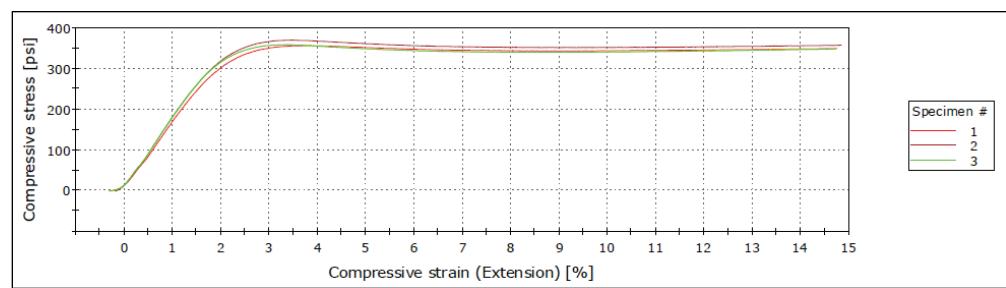


Figure A28. PI Medium 120-min. cure stress-strain curve.



A.2.3 Phase II hydro-insensitivity specimens

Figures A29 through A32 feature the stress-strain curves for the hydro-insensitivity specimens tested in Phase II. Five specimens were analyzed for each formulation.

Figure A29. Phase II Foam-iT! 10 Slow hydro-insensitivity stress-strain curve.

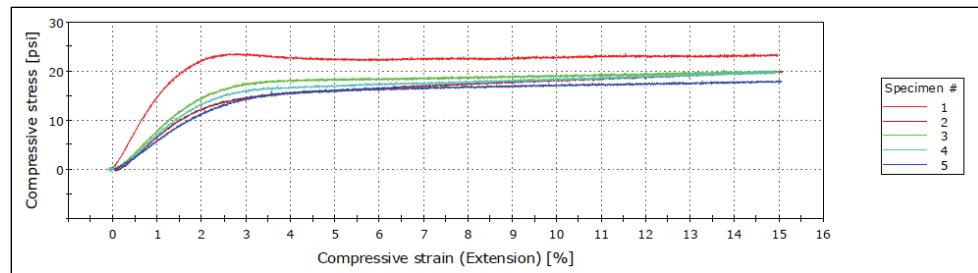


Figure A30. Phase II HMI Batch 3 hydro-insensitivity stress-strain curve.

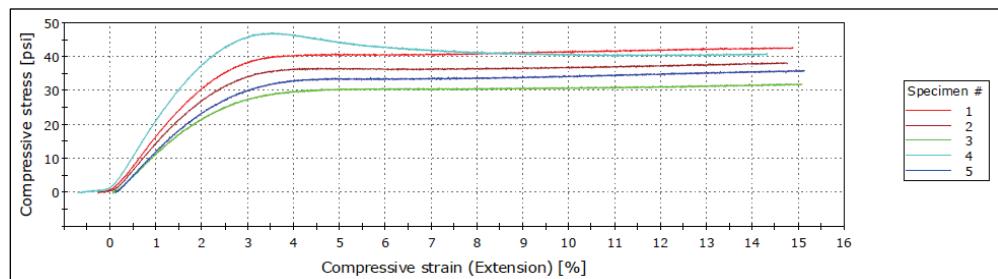


Figure A31. Phase II PI Slow hydro-insensitivity stress-strain curve.

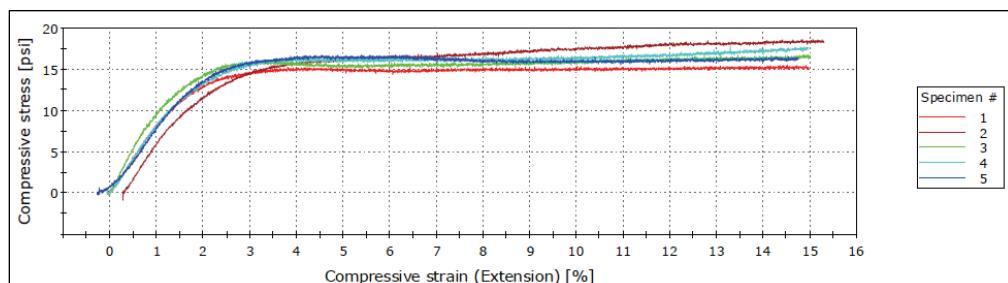
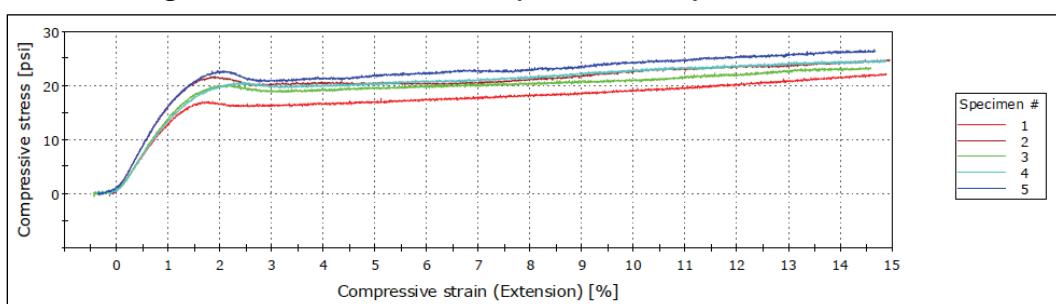


Figure A32. Phase II PI Medium hydro-insensitivity stress-strain curve.



Appendix B: Maximum Compressive Strength

This section includes the average maximum compressive strengths observed during this study. The strain at which the maximum compressive strength occurred is also reported.

B.1 Phase I maximum compressive stress data

Table B1 features the average maximum compressive stress observed for each formulation analyzed during Phase I of this study. Table B2 includes the approximate strains at which these maximum compressive stresses were observed.

Table B1. Phase I maximum compressive stress.

	Maximum Compressive Strength (psi)			
	Overnight Cure	1-hr Cure (Bottom)	1-hr Cure (Top)	Hydro- insensitivity
Foam-iT! 10 Slow	398	348*		10*
NCFI Void-Filling System 24-020	225*	250*†		15*
HMI RR601	180*	140*	175*	25*

* Approximate value.

† Average value of top and bottom specimens for 1-hr cure.

Table B2. Strain at maximum compressive stress.

	Strain at Maximum Compressive Stress - Overnight Cure (%)
Foam-iT! 10 Slow	5.5*
NCFI Void-Filling System 24-020	4.5*
HMI RR601	15†

* Approximate value.

† Increased throughout strain range tested.

B.2 Phase II maximum compressive stress data

This section includes the maximum compressive stress data collected for all of the specimens analyzed during Phase II of this study. The maximum compressive stresses and associated strains for the specimens that were

cured overnight, kinetic compressive stress specimens, and hydro-insensitivity specimens are included.

B.2.1 Phase II overnight cure – “dry” and hydro-insensitivity

Table B3 displays the maximum compressive stress data for the specimens that were prepared both with and without water and cured overnight during Phase II of this study. Table B4 displays the strains at which these stresses were observed. The standard deviations for each formulation are included.

Table B3. Phase I maximum compressive stress – overnight (dry) and hydro-insensitivity specimens.

	Max Compressive Stress - "Dry" (psi)		Max Compressive Stress - Hydro-insensitivity (psi)	
	Average	Std. Dev.	Average	Std. Dev.
Foam-It 10 Slow	475	7.0	20	1.8
Phase II HMI Batch 1	299	11.4	---	---
Phase II HMI Batch 2	332	14.4	---	---
Phase II HMI Batch 3	238	8.1	39	5.2
PI - Slow	393	15.4	17	1.1
PI - Medium	385	9.3	24	1.5

Table B4. Strain at maximum compressive stress – Phase II overnight dry) and hydro-insensitivity specimens.

	Strain at Max Compressive Stress - Dry (%)		Strain at Max Compressive Stress - Hydro-insensitivity (%)	
	Average	Std. Dev.	Average	Std. Dev.
Foam-It 10 Slow	7	0.2	14	1.3
Phase II HMI Batch 1	3	0.1	---	---
Phase II HMI Batch 2	4	0.12	---	---
Phase II HMI Batch 3	3	0.1	13	4.5
PI - Slow	4	0.1	13	3.7
PI - Medium	4	0.2	15	0.1

B.2.2 Phase II maximum compressive stress data – time study

Table B4 and Figure B1 feature the maximum compressive stress data at different cure times. The associated standard deviations are shown in Table B5. The strains at which the maximum compressive stresses are reached for the 120 min specimens are shown in Table B6. For the specimens produced at lower curing times, the stress continued to increase throughout the strain range analyzed. Therefore, the maximum stress was observed at a strain of approximately 15 percent for these specimens.

Table B5. Average maximum compressive stress – kinetic strength study.

Time (min)	Average Maximum Compressive Strength (psi)				
	Foam-iT 10 SLOW	Phase II HMI Batch 1	Phase II HMI Batch 3	Primal Innovation Slow	Primal Innovation Medium
15		21	8		69
20	104				
30	163	47	21		158
45	223		42		212
60	301		71	81	253
120	382		192	274	361

Figure B1. Kinetic maximum compressive stress.

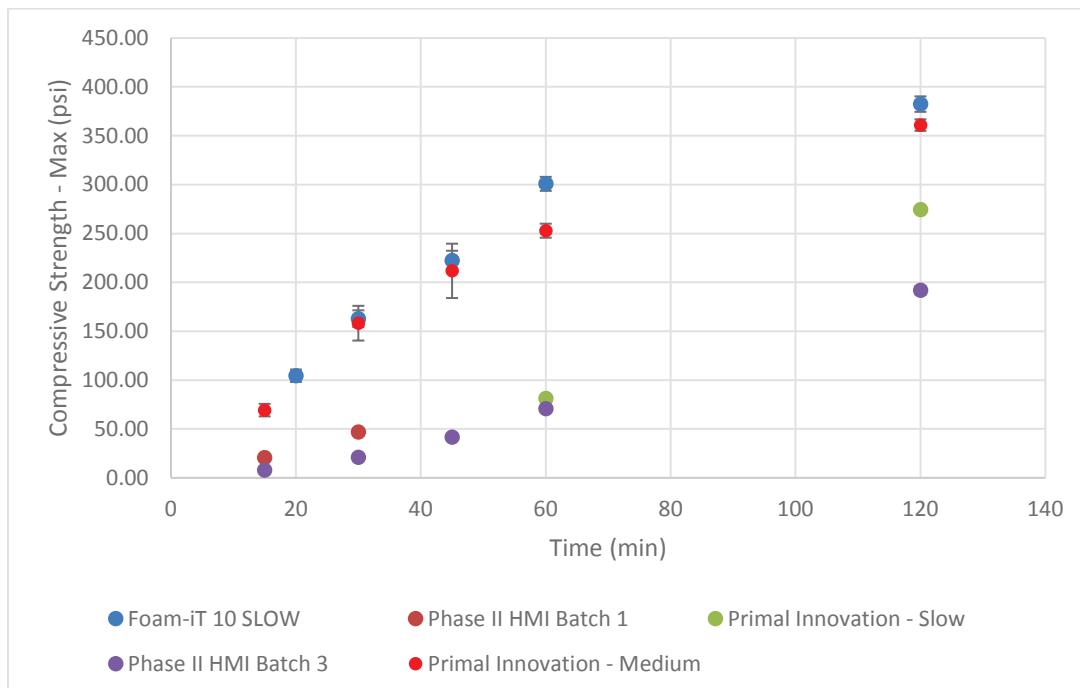


Table B6. Maximum compressive stress standard deviation - kinetic strength study.

Time (min)	Std. Dev. Maximum Compressive Strength (psi)				
	Foam-iT 10 Slow	Phase II HMI Batch 1	Phase II HMI Batch 3	Primal Innovation - Slow	Primal Innovation - Medium
15		0.7	0.4		6.4
20	6.3				
30	8.5	1.0	0.8		17.8
45	9.9		0.5		27.8
60	7.1		0.7	3.8	7.2
120	7.9		4.3	2.0	5.9

Appendix C: Additional Hydro-insensitivity Figures

This section includes additional figures detailing the qualitative issues observed with the hydro-insensitivity specimens produced during Phase II of the study. Specifically, Figure C1 shows that although the majority of the Phase II HMI (Batch 3) hydro-insensitivity specimens were produced with flat bottoms, one specimen was not. Instead, this specimen seemed to mostly detach from the base of the molding cylinder during this curing process. This factor indicates that the formulation may be prone to detachment during field use. Additionally, the other specimens featured hollow bottoms. These specimens would likely experience high strains at relatively low compressive stresses because of this feature.

Figure C1. Bottoms of HMI RR601 hydro-insensitivity specimens.



Figures C2 and C3 show that each of the specimens produced using either of the PI formulations detached from the molding cylinder during the curing process. Also, the cells at the base of the specimens are larger and may deform at a relatively low compressive stresses.

Figure C2. Bottoms of PI Slow hydro-insensitivity specimens.



Figure C3. Bottoms of PI Medium hydro-insensitivity specimens.



The hydro-insensitivity specimens produced for Foam-iT! 10 Slow were produced with flat bottoms. However, this material was fairly brittle, as indicated by the fracturing observed on one of the specimens shown in Figure C4.

Figure C4. Bottoms of Foam-iT! 10 Slow hydro-insensitivity specimens.



REPORT DOCUMENTATION PAGE

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14. ABSTRACT This report focuses on the laboratory study to evaluate a number of foam materials for their suitability as crater-backfill materials. Seven foam formulations were evaluated between the summer of 2015 and the spring of 2016. Four of these materials were commercially available. The remaining formulations were designed specifically to support this project. The materials were analyzed for compressive strength, reactivity, and expansion ratio, in addition to other properties. Ultimately, two foam materials were identified and recommended for future development efforts at the field scale. All of the materials evaluated in this study were deemed hydro-sensitive, as the structure of the material and the critical properties for performance changed when the foam reacted in the presence of water. This issue should be addressed through contingent actions, such as isolation from water sources and adjustments to the formulation in future development efforts.					
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